Monitoring at Ruapehu volcano; can eruptions be predicted?

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Frontispiece

Panoramic view of Crater Lake, Mt Ruapehu

Abstract

Impacts from volcanic eruptions at Ruapehu affect a large number of people and spread over a large area. Knowing when these eruptions are going to occur would be beneficial, but is usually difficult to determine. Monitoring data such as lake water temperature and chemistry, seismicity, ground deformation and gas emissions have been collected at Ruapehu since the 1950s, and can be used to understand volcanic processes and to try to predict eruptions.

At Ruapehu three different styles of volcanic eruptions occur; phreatic, phreatomagmatic and magmatic. These styles are controlled by different processes and interactions within the hydrothermal system and Crater Lake. The eruptive activity at Ruapehu is cyclic with major phreatomagmatic and magmatic eruptions 50 years apart and major phreatomagmatic eruptive episodes 25 years after these. The different styles give rise to different trends within the monitoring data.

Precursor trends within the chemical dataset, especially the Mg/Cl ratio, provide the greatest information about impending eruptions, although, these trends are inconsistent and eruptions can occur without significant changes. Constant Mg/Cl ratios for 6-15 months preceded large phreatomagmatic eruptions during highly active periods (e.g. 1967-1975), and sharply increasing ratios preceded major phreatomagmatic and magmatic eruptions (e.g. 1995). These trends have not occurred again in the monitoring record so may be unreliable. However they appear to relate to certain cyclic eruptive styles and it is possible the constant Mg/Cl ratio trend will occur again, with renewed phreatomagmatic activity.

Polythionic acids also provide useful precursor trends. Sudden decreases in their concentrations precede eruptions at Ruapehu and Poás volcano. This trend is related to large emissions of sulfur dioxide prior to volcanic eruptions. This type of monitoring ceased at Ruapehu in 1988 and it is recommended that it be re-introduced as it may predict eruptions.

Physical monitoring data displays minor and inconsistent trends before and during eruptions. This infers that the vent is open most of the time and magma may pass into the hydrothermal system without significant seismicity or ground deformation.

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Chapter One – Introduction

1.1. Context of Study

Ruapehu is one of New Zealand’s most active volcanoes and is one of the top tourist destinations in the country for skiing and hiking (Ministry of Tourism website, 2008). These two factors combine to make it a dangerous place to visit, with many people being exposed to a large number of hazards. Being able to predict future eruptions would help to mitigate these hazards. The comprehensive monitoring programme at Ruapehu has provided insight into how the volcano operates and may lead to successful predictions of future eruptions.

1.2. Aims and Objectives

The aim of this study is to examine monitoring data from Ruapehu to determine if there are any consistent trends prior to eruptions that could be used to predict future eruptions.

The objectives for this study are:

- To examine historical eruptions to determine the style of activity and its frequency.
- To investigate trends in monitoring data and relate these to physical and chemical processes within the volcanic system, with the view of using them to predict future eruptions.
- To compare Ruapehu with other similar volcanoes around the world to get a better understanding of how crater lakes operate and investigate precursor activity at these volcanoes.
- To assess the likelihood of future eruptions based on current monitoring data.

The ultimate goal is to determine which monitoring technique(s) at Ruapehu give the most consistent warning of an impending volcanic eruption.

1.3. Taupo Volcanic Zone

Ruapehu is a composite stratovolcano located in central North Island, New Zealand and is the southernmost active volcano in the Taupo Volcanic Zone (TVZ) (Figure 1.1). The TVZ is a NNE-SSW trending zone (Spinks *et al.*, 2005), 300 km long and up to 60 km wide, defined by vent positions and caldera structural boundaries. The zone contains late Pliocene to Quaternary arc volcanics, with andesitic activity beginning at c. 2 Ma and rhyolitic activity at c. 1.6 Ma (Houghton *et al.*, 1995). The TVZ is thought of as a currently active volcanic arc and back arc basin (Cole, 1990), extending from Ruapehu in the south to White Island in the north (Spinks *et al.*, 2005), due to the oblique collision of the Pacific and Australian plates. The relative instantaneous pole of rotation for these two plates is located at 62° S, 174° E and rotation is estimated to be 1.27°/Ma (Chase, 1978). The Pacific plate is being subducted at a rate of 42 mm/y (DeMets *et al.*, 1990) beneath the Australian plate with the boundary located offshore east of the North Island. The subduction is orthogonal at the Tonga-Kermadec trench, north of the TVZ and becomes more oblique further south until the South Island where continental collision takes place and movement is taken up by dextral movement on the Alpine Fault (Cole, 1990). The spreading across the TVZ, currently 7 mm/y (Acocella *et al.*, 2003), has produced crustal thinning of up to 15 km (Wilson *et al.*, 1995), and has resulted in high heat flow within the TVZ (Bibby *et al.*, 1995).

The eastern and western margins of the TVZ are poorly defined as they have been covered by material erupted from the TVZ (Cole, 1990). It appears that the eastern margin has remained stationary for the past 0.34 Ma (Wilson *et al.*, 1995). The northern boundary was thought to stop at White Island, however new information shows younger volcanism occurs north of White Island and continues off the edge of the continental crust (Wilson *et al.*, 1995). The northwest margin of the TVZ merges into the southern end of the Coromandel Volcanic Zone (CVZ). The CVZ was active before the TVZ, from early Miocene (c. 23 Ma) to Pleistocene (c. 0.8 Ma) and comprises basalts, andesites, dacites and rhyolites (Cole, 1990).

The TVZ has formed in two unequal stages as proposed by Wilson *et al.* (1995). The first stage is described as the old TVZ, and represents activity before the Whakamaru eruptions (c. 2 Ma to 0.34 Ma). The second stage is described as the young TVZ, and represents activity after the Whakamaru eruptions (c. 0.34 Ma to present). Details of volcanic activity within the old TVZ have been obscured by the emplacement of widespread ignimbrites and related airfall deposits of the Whakamaru-group eruption (Wilson *et al.*, 1995). Wilson *et al.* (1995) also uses the term modern TVZ to describe volcanic activity from c. 65 ka to present.

The modern TVZ is divided into three sections along its length based on composition (Houghton *et al.*, 1995; Spinks *et al.*, 2005) (Figure 1.1 B). The northern section extends from Edgecumbe to White Island and comprises andesite and dacite volcanoes. The southern section also has andesitic compositions and is known as the Tongariro Volcanic Centre. The 125 km central section from Okataina to Taupo (Spinks *et al.*, 2005) contains eight caldera centres with related ignimbrites as a result of rhyolitic volcanism. High-alumina basalts also occur in this section and are mainly fissure controlled (Cole, 1990). The difference in composition between the lateral and central sections is due to partial melting of older CVZ volcanic and plutonic rocks at depth within the central section of the TVZ (Cole, 1990).

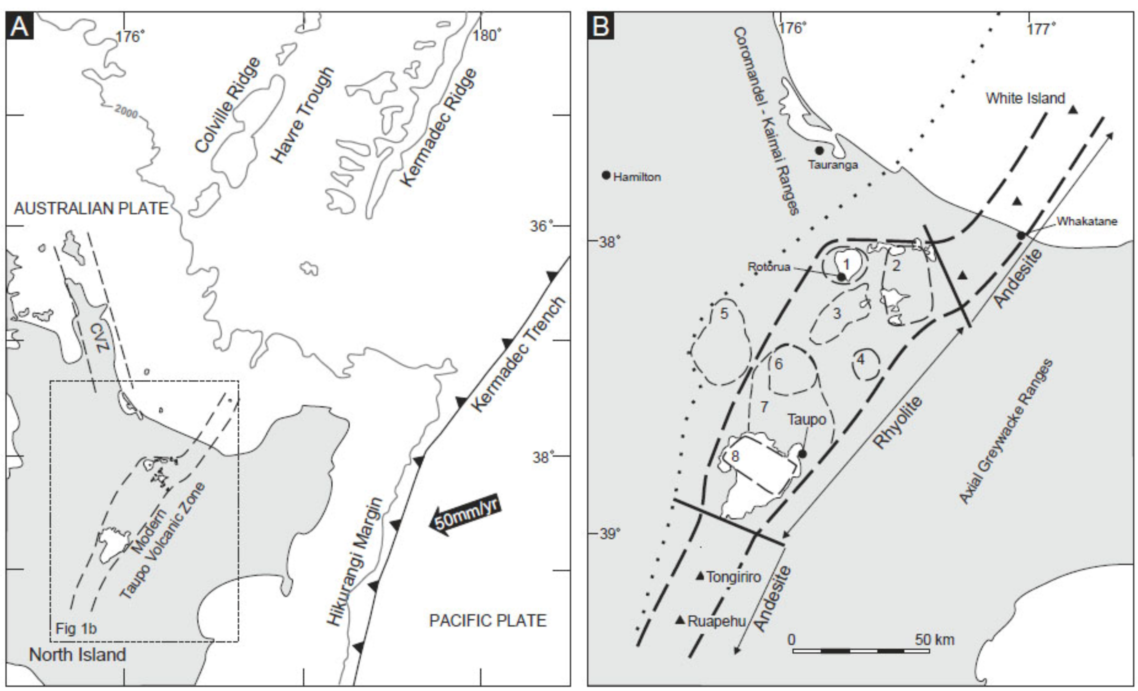


Figure 1.1: (A) Setting of the Taupo Volcanic Zone (TVZ) in relation to the rest of the North Island. (B) Map of TVZ showing calderas and compositional segmentation into andesitic and rhyolitic segments. Calderas: (1) Rotorua; (2) Okataina; (3) Kapenga; (4) Reporoa; (5) Mangakino; (6) Maroa; (7) Whakamaru; (8) Taupo. Tongariro Volcanic Centre includes Ruapehu and Tongariro (from Spinks *et al.*, 2005).

1.4. Tongariro Volcanic Centre

Ruapehu is one of four large dominantly andesitic composite volcanoes within the Tongariro Volcanic Centre (TVC), at the southern end of the TVZ. The other three volcanoes are Kakaramea, Pihanga and Tongariro. There are also three smaller cones: Mangakatote, Hauhungatahi and Pukeonake and four small craters near Ohakune (Cole, 1990) (Figure 1.2). The time at which activity started in the TVC is not precisely known, but Hauhungatahi is the oldest cone with a preferred $^{40}Ar/^{39}Ar$ age between 860-900 ka (Gamble *et al.*, 2008). Within the TVC there are two main structural trends: (1) an older NW-SE trend defined by the vents of Kakaramea, Pihanga and older Tongariro; and (2) a younger NNE-SSW trend defined by younger vents of Tongariro and Ruapehu (Cole, 1978; Graham and Hackett, 1987). Cross fractures are restricted to the southern end of Ruapehu (Cole, 1978).

The formation of andesites in the TVC is thought to be a multistage process involving: (1) dehydration of the slab during subduction; (2) partial meting of the mantle wedge to produce tholeiitic basalt; and (3) fractionation of basalt in the upper mantle or lower crust to produce andesite (Cole, 1978, 1990).

Ruapehu volcano has an approximate volume of 110 km^3 which is mostly andesite lava flows and pyroclastic material. Another 100 km^3 of pyroclastic and laharic ring plain deposits surround the volcano (Hackett and Houghton, 1989). Graham and Hackett (1987) recognise four main periods of cone building which span c. 250 ka, and the formations of these periods are known as the Ruapehu Group. The formations are (from oldest to youngest) Te Herenga, Wahianoa, Mangawhero and Whakapapa (Figure 1.2). The Te Herenga Formation forms the early Ruapehu cone and is now only visible on Pinnacle Ridge. One K-Ar date of 230 ka has been obtained for this formation (Graham and Hackett, 1987). The Wahianoa Formation contains voluminous lava flows and tuff breccias and has been dated at 134 ka (Hales, 2000). The Mangawhero Formation forms most of Ruapehu's high peaks, and is 96 % lava flows and tuff breccia. Two imprecise K-Ar ages of 24 and 36 ka have been determined (Graham and Hackett, 1987). The Whakapapa Formation contains all deposits younger than 10 ka and represents eruptions from the summit vents (Graham and Hackett, 1987).

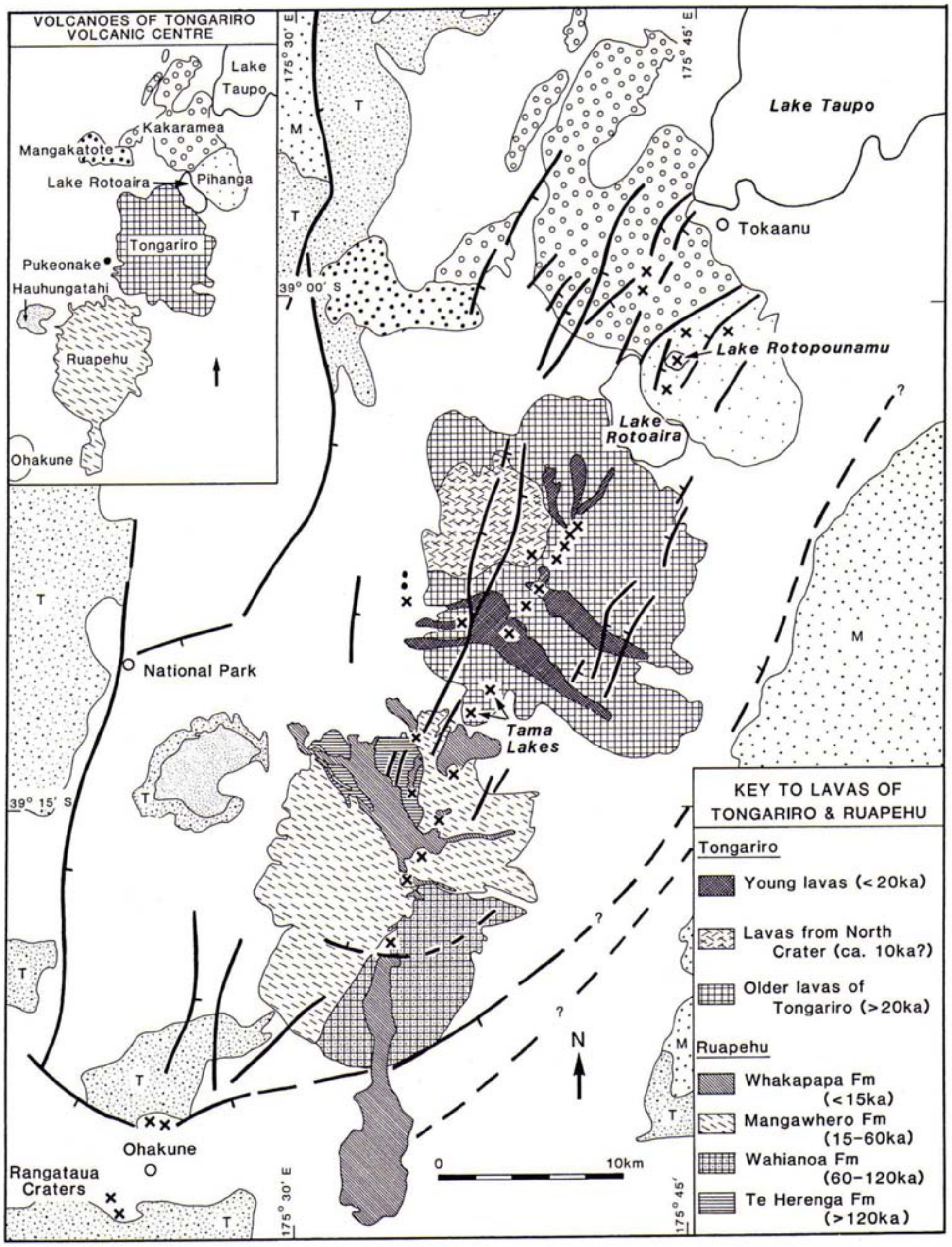


Figure 1.2: Volcanoes of the Tongariro volcanic centre. Crosses indicate main (<50 ka) vents. *M*, Mesozoic greywacke-argillite; *T*, Tertiary sediments (from Cole, 1990).

The summit region contains four craters: North; East; West; and Girdlestone (Cole and Nairn, 1976) (Figure 1.3), with historical activity taking place at two vents below Crater Lake within the West Crater (Figure 2.2).

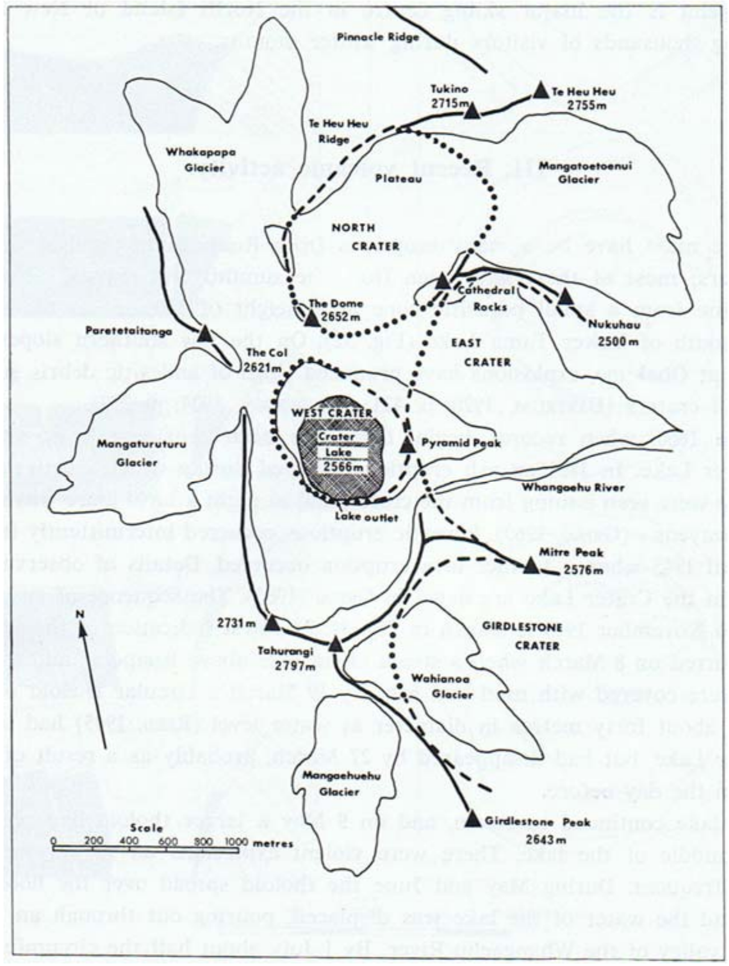


Figure 1.3: Summit region of Ruapehu showing locations of North, East, West and Girdlestone Craters. *Bold lines* represent ridges; *dashed lines,* exposed crater rims; *dotted lines,* inferred crater rims (from Cole and Nairn, 1976).

1.5. Ruapehu Eruptive History

Activity at Ruapehu from 1950 to 2008 is summarised in Figure 1.6 and Table A.1. The earliest report of volcanic activity at Ruapehu was in 1861, and may have involved emplacement of a lava dome. This eruption sent a lahar down the Whangaehu River (Neall *et al.*, 1999). There was another major eruption reported in 1895 which also sent a lahar down the Whangaehu River (Neall *et al.*, 1999). Between March and July 1945, a lava dome was emplaced under Crater Lake. The rise of the dome displaced the lake water down the Whangaehu River (Houghton *et al.*, 1987); however, no lahars were recorded (Neall *et al.*, 1999). By July 1945 the dome had completely filled the crater and a small vent was established on the dome. The vent became enlarged by explosive ash eruptions, peaking in

August when ash fell 90 km to the SSW (Houghton *et al.*, 1987), until November when it was approximately 100 m wide and 300 m deep (Stevenson, 1992). On 6 November the largest eruption took place and destroyed the remaining parts of the dome. A lake began to form in the crater and by 1953 it had reached the pre-1945 level (Houghton *et al.*, 1987).

The 1945 eruptions left a weak tephra dam over the lake outlet. On 24 December 1953 the dam failed and sent 1.82×10^6 m^3 of lake water (Hales, 2000) down the Whangaehu valley. This lahar destroyed the Tangiwai rail bridge just minutes before the Wellington-Auckland express arrived. As a result, 151 passengers died.

Between 1945 and 1995 only minor phreatic and phreatomagmatic eruptions occurred with two major eruptions on 22 June 1969 and 24 April 1975. The phreatomagmatic eruption on 22 June 1969 covered the summit plateau with ash and created lahars down the Whakapapanui, Whakapapa, Mangaturuturu and Whangaehu valleys (Healy *et al.*, 1978). The phreatomagmatic eruption on 24 April 1975 was between two (seismic energy) and four (ejecta volume) times larger than the 1969 eruption (Nairn *et al.*, 1979). This eruption produced lahars down Whakapapanui, Whakapapaiti, Mangaturuturu and Whangaehu valleys, which caused the lake level to drop by 8 m (Nairn *et al.*, 1979). A further eruption on 27 April deposited mud and ash on the upper slopes and produced a small lahar in the Whangaehu valley (Sherburn *et al.*, 1999). Small phreatic and phreatomagmatic eruptions occurred during January 1982, but were confined to the crater basin (Sherburn *et al.*, 1999). On 8 December 1988 a moderate sized phreatic eruption occurred which ejected water, mud and rocks 1.1 km to the northeast of the vent and produced a small lahar which travelled down the Whangaehu valley.

In early 1995 small phreatic eruptions occurred at Ruapehu. On 23 September a much larger phreatomagmatic eruption occurred (Figure 1.4). This eruption ejected mud, ash and bombs onto the summit plateau with some ash to the northeast of the crater, it also produced lahars down the Whangaehu, Whakapapanui, Whakapapaiti and Mangaturuturu valleys (Scott *et al.*, 1998). Eruptions over the next few days removed most of the lake water. On 11-12 October, the largest sustained eruption occurred and removed the remaining water from Crater Lake; activity also changed from phreatomagmatic to magmatic (Bryan and Sherburn, 1999). The change in the style of activity produced large ash plumes that rose 8-11 km (Bryan and

Sherburn, 1999). By mid-November activity had decreased and Crater Lake began to reform. In June 1996 eruptive activity resumed and emptied Crater Lake. Over the next six weeks distinct magmatic eruptions occurred, depositing ash 200 km from the volcano and bombs to 1.5 km from the vent (Bryan and Sherburn, 1999). By September activity had decreased (Sherburn *et al.*, 1999) and Crater Lake began to reform. Minor phreatic and phreatomagmatic activity continued until the end of 1998. The 1995-1996 eruptions left a 6-7 m high tephra dam across the lake outlet, similar to the one that formed during the 1945 eruptions (Manville and Cronin, 2007; Smithsonian Institution, 2009b). On 18 March 2007 the dam failed and sent a lahar down the Whangaehu valley and out to sea.

Figure 1.4: Phreatomagmatic eruption on 23 September 1995 (from Te Ara website, 2009).

On 4 October 2006 a small hydrothermal eruption occurred with wave action reaching 4-5 m above the lake surface. This eruption was preceded by a magnitude 2.8 volcanic earthquake (Smithsonian Institution, 2009b). No further activity was reported until a moderate hydrothermal eruption on 25 September 2007. The eruption ejected ash, mud and bombs 2 km north of Crater Lake, and produced lahars down the Whangaehu valley and Whakapapa ski field (Figure 1.5). One person was injured when a bomb crashed through Dome Shelter.

Figure 1.5: Photograph of Ruapehu summit plateau showing the ash deposits and lahar on the Whangaehu glacier after a hydrothermal eruption on 25 September 2007 (from GNS Science website, 2009).

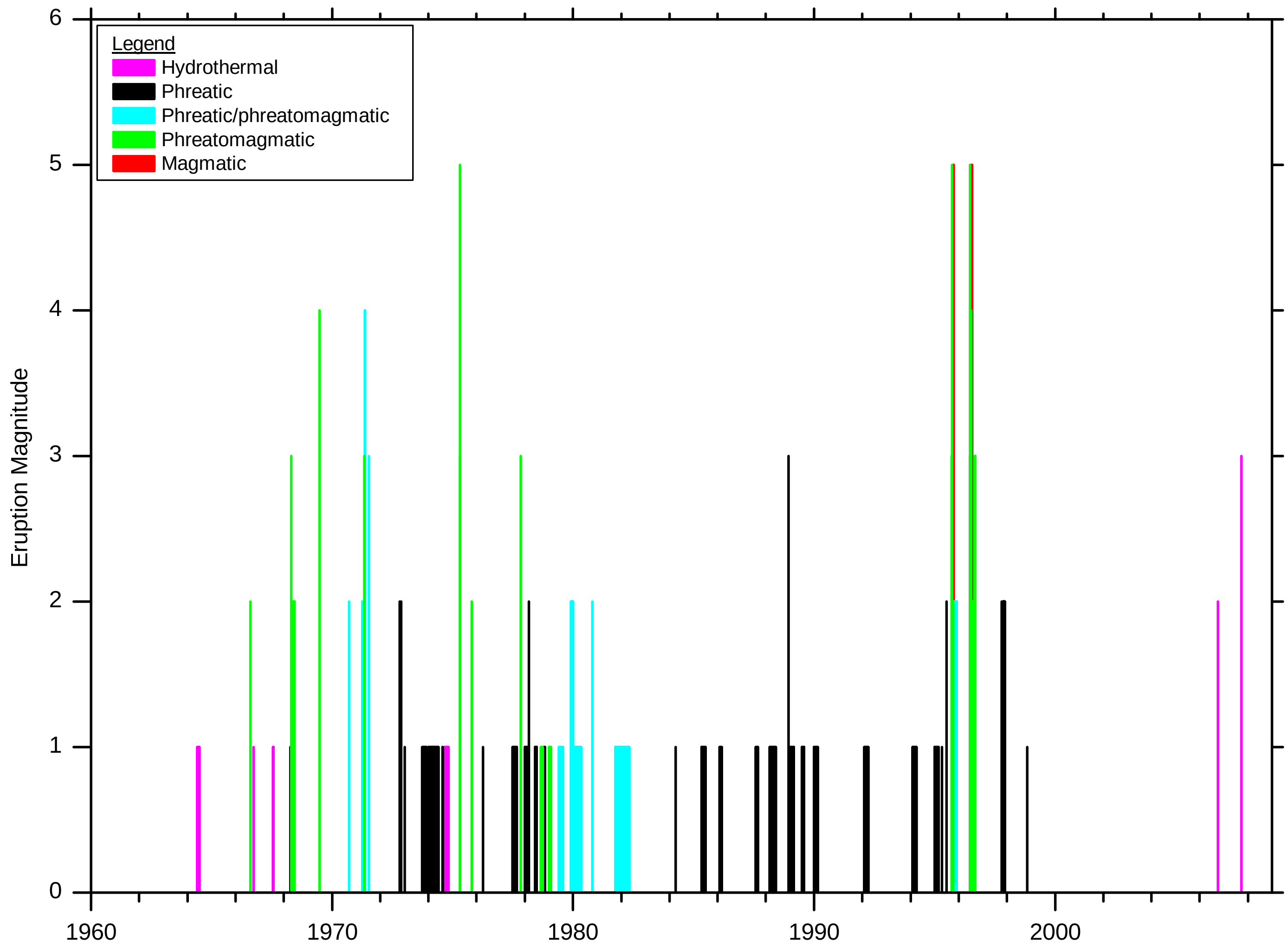


Figure 1.6: Graph showing eruptive magnitude and style at Ruapehu, 1960-2008. The magnitude is a semi-quantitative estimate based on observed effects (Table A.2), (adapted from Houghton *et al.*, 1987; Stevenson, 1992; with additional data from the New Zealand Volcanological Records).

Chapter Two – Crater Lakes

2.1. Crater Lake Processes

Approximately 12 % of the world's 714 Holocene age volcanoes have volcanic lakes (Pasternack and Varekamp, 1997). These lakes are vastly different from each other; some may be highly acidic, and others neutral. They can differ in the amount and type of dissolved chemical constituents, and they may be chemically well mixed to their bases or stratified (Delmelle and Bernard, 2000). These differences are influenced by the volcanic inputs, which consist of hot gas and liquids from interaction between magmatic fluids and water (Delmelle and Bernard, 2000). Ultimately, volcanic lakes are the surface expression of a hydrothermal reservoir between the surface and the underlying magma (Pasternack and Varekamp, 1997).

The volcanic lake's existence is based on the balance between volcanic/hydrothermal heat fluxes and atmospheric cooling. This balance can be determined using the energy-balance box model (Figure 2.1). For a simple steady state volcanic lake, mass balance demands that:

$$W_{volcanic} + W_{meteoric} = W_{evap} + W_{outflow} + W_{seep}$$

where $W_{volcanic}$, $W_{meteoric}$ are the volcanic and meteoric water fluxes into the lake, and W_{evap}, $W_{outflow}$ and W_{seep} are the evaporation, outflow and seepage fluxes of the lake (Pasternack and Varekamp, 1997). The energy balance can be expressed as:

$$E_{cond}^{volc} + E_{volc} + E_{rad}^{sun} + E_{rad}^{atm} = E_{rad}^{lake} + E_{evap} + E_{cond}^{lake} + E_{meteoric}$$

where E_{cond}^{volc} is the conductive heat input from a shallow magma body, E_{volc} is the enthalpy of the volcanic/hydrothermal flux, E_{rad}^{sun} is the short wavelength solar flux, and E_{rad}^{atm} is the long wavelength radiative input from the atmosphere. The energy outfluxes, E_{rad}^{lake}, E_{evap}, E_{cond}^{lake} and $E_{meteoric}$ are, respectively, the lake surface long wavelength radiation, evaporation, conduction and heating of meteoric fluxes up to the lake's temperature (Pasternack and Varekamp, 1997).

This is a very simple generic model of volcanic lake persistence. In some volcanoes such as Ruapehu a heat pipe between the magma and lake plays an important role and increases the energy influx into the lake.

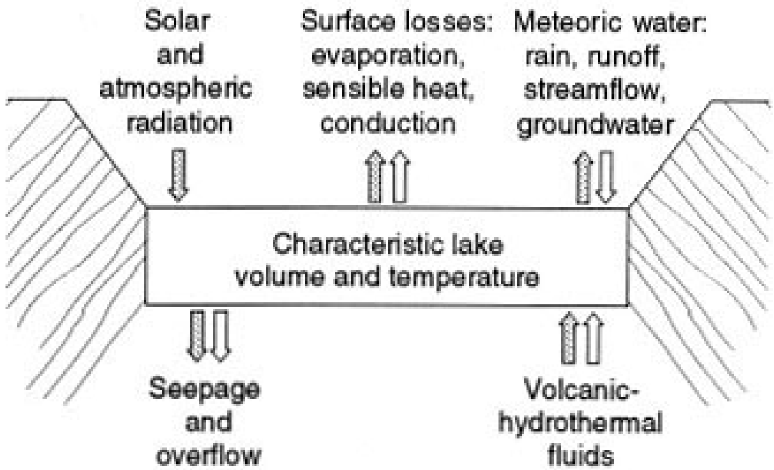


Figure 2.1: Cartoon showing fluxes of water (white arrows) and heat (shaded arrows) into and out of a volcanic lake as used in the "box model" (from Delmelle and Bernard, 2000).

2.1.1. Ruapehu Model

The above box model is mostly correct for Crater Lake, however Hurst *et al.* (1991) concluded that the lake was being heated by more than just magmatic steam, and proposed a heat pipe mechanism to provide additional heating. A heat pipe transfers heat in an efficient manner by using vapour-liquid counterflows and is a fundamental component in geothermal systems (Hurst *et al.*, 1991). Below the lake the magma body and vent are enclosed by a single-phase vapour zone. This region is enclosed by a two-phase liquid-vapour zone which is enclosed by a single-phase liquid zone (Christenson and Wood, 1993), with the heat pipe operating between the single-phase vapour and two-phase liquid-vapour zones (Figure 2.2). The heat pipe proposed by Hurst *et al.* (1991) consists of steam rising, condensing and liquid falling under gravity as a counter flow through the porous fractured zone under Crater Lake.

Hurst *et al.* (1991) proposed that the heat pipe mechanism and heat transfer via magmatic steam work in combination to transfer heat from the magma to the lake. In addition to the heat pipe and magmatic steam transfer, Christenson and Wood (1993) recognised that downward circulation of lake water into the two-phase liquid-vapour zone also plays a role in the heat transfer from the magma to the lake.

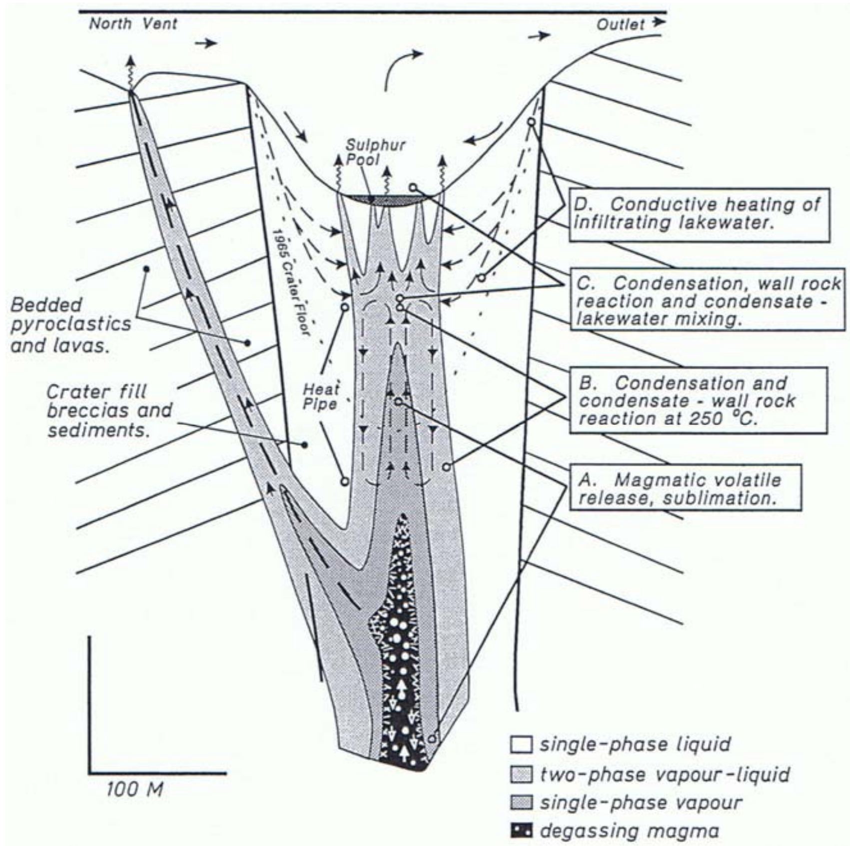


Figure 2.2: Physical model of Ruapehu's vent system. *Heavy near-vertical lines* denote the boundaries of the central vent, and the *dotted line* in the central vent complex represents the approximate bathymetric profile in 1965 (from Christenson and Wood, 1993).

Hurst *et al.* (1991) noted that within Crater Lake there is a cyclic heating and cooling pattern with heating for two months and cooling lasting for 6-12 months. They suggest that a layer of sulfur on the bottom of the lake could play an important role in the cyclic heating and cooling. The temperatures at the bottom of the lake would be sufficient for at least part of the sulfur to be liquid (Hurst *et al.*, 1991). The viscosity of liquid sulfur is highly temperature dependent (Figure 2.3). Below 160°C the sulfur has a low viscosity. Between 160 and 200°C the viscosity increases dramatically, and above 200°C it decreases (Hurst *et al.*, 1991). Therefore, the heat flow into Crater Lake will depend on the temperature of the liquid sulfur layer. With temperatures below 160°C both heat and gas can be transferred to the lake, but as temperature increases the viscosity of the sulfur will increase, which will cause a cooling in the lake, as there is no longer a heat sink at the surface. As the temperature continues to increase the viscosity of the sulfur will decrease and heating of the lake will continue. Furthermore, the confining pressure deeper in the vent is likely to exceed hydrostatic pressure from time to time. During times when the liquid sulfur has high viscosity the system can overpressure and cause an eruption from a cold lake (Christenson and Wood, 1993). One example of this was the phreatic eruption on 8 December 1988.

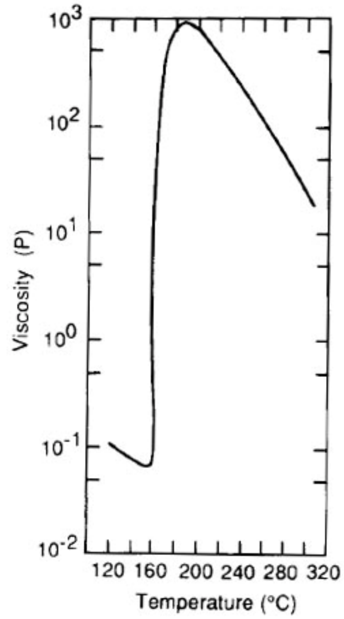


Figure 2.3: Viscosity of liquid sulfur as a function of temperature (from Hurst *et al.*, 1991).

2.2. Types of Eruptions from Crater Lakes

2.2.1. Phreatic Eruptions

Phreatic eruptions occur more frequently at Ruapehu than other types of eruptions, averaging one every two to three years. These eruptions occur when magma and water come into contact, and the water is flashed to steam instantaneously (Browne and Lawless, 2001). Unlike phreatomagmatic eruptions, phreatic eruptions only eject country rock and lake sediments and not juvenile material. Hydrothermal eruptions also occur at Ruapehu when hot water flashes to steam as a result of a sudden pressure reduction (Browne and Lawless, 2001). The energy provided from the steam is enough to fracture and eject country rock. These eruptions differ from phreatic eruptions in that no mass or energy is directly derived from magma (Browne and Lawless, 2001). This leads to confusion, as it is very hard to determine the difference between these two styles of eruption, which may only be possible by investigating any hydrothermal minerals formed during the eruption (Browne and Lawless, 2001). As a result of this, there are many different definitions for both styles within the literature.

These styles of eruption only affect the local area (Barberi *et al.*, 1992), with most of the volcanic material falling within the summit plateau, and with occasional lahars down the Whangaehu and Whakapapa valleys; hence, they are less hazardous than other styles of eruption.

2.2.2. Phreatomagmatic Eruptions

A phreatomagmatic eruption results from the volumetric expansion of water, after it has been in contact with magma. The water source can be seawater, groundwater, or in the case of Ruapehu: a crater lake.

The ascending magma has a temperature well above the boiling point of water so when the two come into contact, the water vaporises at explosive rates (Sheridan and Wohletz, 1983). This process rapidly converts thermal energy into mechanical energy. Initially, a small volume of water is vaporised due to contact with magma. The vaporisation of the water fragments the magma, which increases the surface area of contact between water and magma. This leads to further vaporisation of water in a feedback process and the system explodes (Sheridan and Wohletz, 1983). In many volcanoes the amount of water available increases through the eruption, however at Ruapehu the amount of water decreases as Crater Lake disappears (Hales, 2000) and the eruptions become more magmatic.

The processes involved in phreatomagmatic fragmentation have been studied by conducting fuel-coolant interaction (FCI) experiments. In these experiments a cold volatile fluid (coolant) and a hot fluid (fuel) are mixed, with both explosive and non-explosive results depending on the rate of heat transfer (Morrissey *et al.*, 2000). The common fuel used is a thermite melt which simulates basaltic magma (Morrissey *et al.*, 2000). The experiments have shown that the optimum water to magma ratio for explosive eruptions for basaltic magma is 0.3 (Sheridan and Wohletz, 1983). With too much water the explosion is buffered and quenching of the magma occurs; with too little water it escapes as steam and has no effect on the magma (Hales, 2000).

Other mechanisms may also influence the formation of phreatomagmatic explosions, these are: (1) explosive release of magmatic volatiles; (2) explosive expansion of steam following enclosure of water in magma; (3) explosive expansion of steam formed at the magma-water interface; and (4) cooling contraction of the magma (Kokelaar, 1986).

During the eruption ejecta is directed vertically and laterally. Vertically directed ejecta is fine grained and will be in a steam or water rich plume. Laterally directed ejecta will form base surges (Morrissey *et al.*, 2000). Cypressoidal (cock's tail) explosive jets of ash and billowing clouds of steam are also common.

2.2.3. Magmatic Eruptions

Magmatic eruptions do not occur through crater lakes although they are worth mentioning here as they have occurred at Ruapehu three times (1861, 1945 and 1995-1996) in the historic record.

Explosive magmatic eruptions occur when exsolution of dissolved gases (mainly H_2O) from magma occurs rapidly. As the magma rises it experiences a decrease in pressure which allows bubbles to form and expand. When they occupy 70-80 % of the volume, fragmentation takes place (Cashman *et al.*, 2000). At this point the magma transforms from a liquid with bubbles to a gas with suspended blobs of liquid (Cashman *et al.*, 2000), which accelerate out of the vent and into the plume.

Fragmentation may result from rapid acceleration or by rapid decompression of the magma (Cashman *et al.*, 2000), and can be classed as brittle or ductile (Mader, 1998). The mechanism is controversial as it is not possible to view the process first hand. The main controls on the explosive behaviour are the relative rates of bubble growth, magma transport and gas loss (Cashman *et al.*, 2000).

Pyroclasts formed from magmatic eruptions are vesicular and have a pumiceous form (Hales, 2000), and can lead to insights into which fragmentation mechanism is operating (Cashman *et al.*, 2000).

Chapter Three – Current Monitoring at Ruapehu

All the monitoring carried out at Ruapehu is by GNS Science (or its predecessor the Department of Scientific and Industrial Research) through the GeoNet project. The current types of monitoring include: lake water chemistry and temperature, seismicity, ground deformation and gas emissions. Each is described below. They also use visual observations to help tie everything together. GNS Science staff visit Crater Lake at least once a month to observe the lake, to take temperature measurements and to collect water samples for chemical analysis. There are also two webcams pointed at Ruapehu which take still photographs at 30 minute intervals; one is located on the west near National Park Village, and the other newly installed one on the east, which is also capable of taking video if required.

3.1. Lake Water Chemistry

Crater Lake is a calorimeter and chemical trap for heat and mass flows from the magmatic-hydrothermal system below (Scott *et al.*, 1998), and the monitoring of the chemical composition of the lake can provide insights into future volcanic activity.

Routine surveillance of Crater Lake chemistry started in 1970 (Christenson, 2000), with samples collected by GNS Science staff at least monthly on surveillance visits. The samples are analysed at their laboratory for various different chemicals. After investigation on the effects of volcanic activity on lake chemistry by Giggenbach (1983) it was determined that chloride and magnesium concentrations were the most important constituents.

Chloride is derived from fumarolic steam, mainly as HCl (Giggenbach and Glover, 1975), from fumaroles on the crater floor and walls. Giggenbach (1983) suggested that the variations in chloride concentration are proportional to the amount of steam required to bring about the changes in temperature of the lake. Chloride is also associated with degassing of the volcano.

Magnesium is derived from fresh magmatic material (Giggenbach and Glover, 1975). Interaction of fresh magma and hot acidic lake water will increase the magnesium concentration, which may prove to be a valuable indicator of future eruptions.

Heavy rainfall, runoff and snow melt may enter the lake and dilute the chloride and magnesium concentrations. However, by forming the Mg/Cl ratio, the concentrations are independent of dilution (Giggenbach, 1983). This ratio will increase with addition of magnesium, decrease with addition of chloride and remain constant during low fumarolic or eruptive activity (Giggenbach, 1983).

A number of other chemicals and parameters are also monitored, including pH, but these are not thought to be as important as magnesium and chloride.

3.2. Lake Water Temperature

Measuring the temperature of Crater Lake is important for overall surveillance as it may indicate impending volcanic activity. As the heat flows out of the conduit below the lake, it causes an overall increase in the lake temperature. Therefore trends in lake temperature may indicate changes in volcanic activity below (Trunk and Bernard, 2008). However, this relationship is very complex.

The first recorded temperature from Crater Lake was in 1895 (Gregg, 1960), with more frequent recordings taken after the 1945 eruptions, and at least monthly recordings taken from the 1960s onward. These monthly temperature recordings are taken by GNS Science staff using a thermocouple during their surveillance visits to the lake. The temperature has been monitored continuously in the past by the use of temperature loggers, with the first attempt in 1969 (Hurst and Vandemeulebrouck, 1996). In the 1970s, buoys with high frequency radio transmitters floating on the lake were used, but only lasted three months. In the 1990s smaller and cheaper recorders were used, but data were recorded on-site, so they were not suitable for identifying precursor activity (Hurst and Vandemeulebrouck, 1996).

The use of satellite imaging such as ASTER (Advanced Spacebourne Thermal Emission and Reflection Radiometer) has also been used to determine temperatures of Crater Lake (e.g.

Joyce *et al.*, 2008). Satellite methods offer a way of getting direct measurements from difficult locations.

The temperatures recorded are not always a direct indication of volcanic activity, as external factors such as precipitation, snow melt and increased overflow can lower the lake temperatures.

3.3. Seismicity

Understanding seismic activity at volcanoes is important for ongoing monitoring and prediction of eruptions, as volcanic eruptions are preceded and/or accompanied by anomalous seismic activity (GeoNet website, 2009). Volcanic seismicity (earthquakes and tremor) is magmatic-induced seismicity and occurs at or near volcanoes, generally within 10 km (McNutt, 2000). If magmatic fluids are not involved then it is termed volcano-tectonic seismicity (Sherburn *et al.*, 1999).

The earliest seismic observations at Ruapehu were during the 1945 eruptions and since then the seismic network has evolved (Sherburn *et al.*, 1999). Currently the network consists of eight seismic sites (GeoNet website, 2009) within 20 km of the vent, with Dome Shelter (DRZ) being the closest (Figure 3.1). There are a range of different seismographs with data transferred to the Chateau Observatory at Whakapapa Village, then to the GNS Science Observatory at Wairakei (Sherburn *et al.*, 1999). Along with the permanent network there are a number of temporary seismographs within the surrounding area. Before 1990 the data were transmitted via analog radios. Since then, data have been recorded digitally (Sherburn *et al.*, 1999) on seismographs and can be displayed as real-time seismic-amplitude measurements (RSAM) and seismic spectral-amplitude measurements (SSAM). RSAM displays the overall seismic amplitude over ten minute periods and SSAM displays the relative signal size in different frequency bands (GeoNet website, 2009).

Sherburn *et al.* (1999) have described the seismicity at Ruapehu based on the appearance and frequency of the waveforms at monitoring sites. They classify volcanic earthquakes by their harmonic waveform and frequency range of 1.8-2.3 Hz with a peak at 2 Hz. These 2 Hz earthquakes are the most common at Ruapehu. Wideband volcanic earthquakes with frequencies of 2 to 10 Hz first appeared on 15 October 1995.

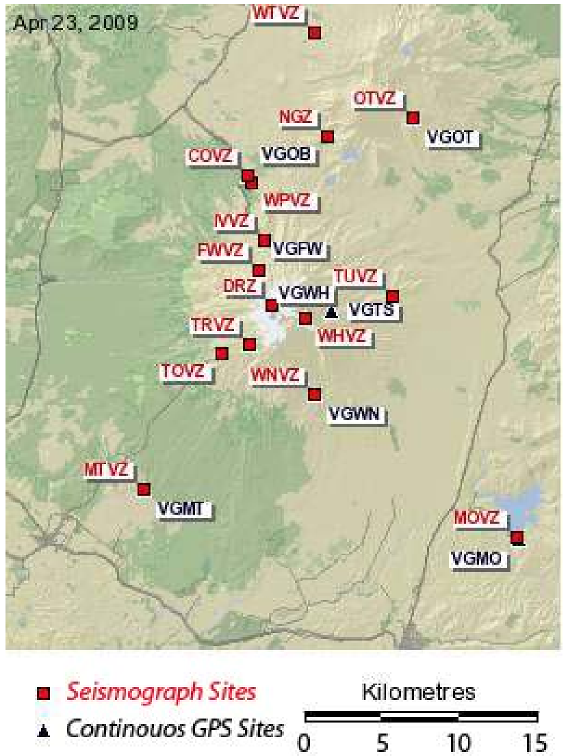


Figure 3.1: The Ruapehu monitoring network map showing most of the sites as at 23 April 2009. Seismograph sites are: (COVZ) Chateau Observatory; (WPVZ) Whakapapa; (FWVZ) Far West T-Bar; (DRZ) Dome Shelter; (TUVZ) Tukino; (TRVZ) Turoa; (WNVZ) Wahianoa; (WHVZ) Whangaehu Hut. Continuous GPS sites are: (VGOB) Chateau Observatory; (VGFW) Far West T-Bar; (VGWH) Whangaehu; (VGTS) Tukino Skifield; (VGWN) Wahianoa. Microphone sites are: (IVVZ) Iwikau Village; (TOVZ) Turoa Road End (modified from GeoNet website, 2009).

During the late 1980s, 3 Hz tremor was common, but only recorded at DRZ, suggesting that the source was close to the summit and shallower than the 2 Hz source (Sherburn *et al.*, 1999). From December 1993, 7 Hz tremor was recorded, again only at DRZ, suggesting a shallow source depth (Sherburn *et al.*, 1999). Wideband and sub-1 Hz tremor were first recorded during the 1995 eruption period with the sub-1 Hz tremor disappearing in early October 1995.

Sherburn *et al.* (1999) also classified volcano-tectonic earthquakes as earthquakes that are not related to eruptions or magmatic fluids and are in fact tectonic earthquakes that occur close to the active vent. Shallow volcano-tectonic earthquakes originate below Crater Lake and are only recorded at DRZ.

A model produced by Sherburn *et al.* (1999) shows the vent system at Ruapehu before the 1995-1996 eruption period, with the likely sources of the seismicity (Figure 3.2).

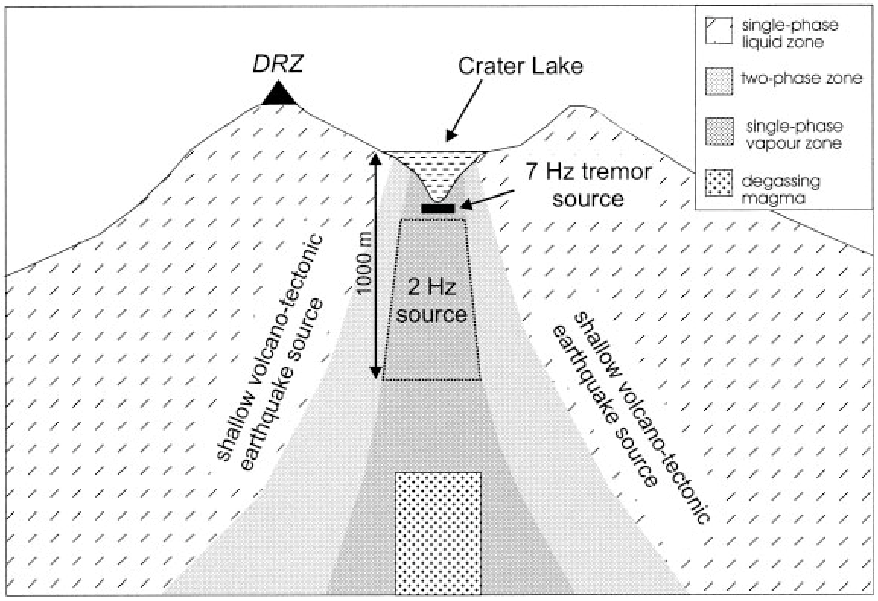


Figure 3.2: Cartoon of the structure of the vent system at Ruapehu in January 1994. Inferred locations of the 2 Hz, 7 Hz tremor and shallow volcano-tectonic earthquake sources are shown. The position of DRZ is shown for reference (from Sherburn *et al.*, 1999).

3.4. Ground Deformation

The ground surface around a volcano usually deforms before, during or after an eruption as a result of the influx or withdrawal of magma below the vent. Thus, ground deformation may signal the start of a new eruptive episode. Techniques used by GNS Science (or its predecessor the Department of Scientific and Industrial Research) at Ruapehu have included geodetic levelling, electronic distance measurements (EDM) and continuous global positioning measurements (GeoNet website, 2009). Lake levelling, which uses the lake as a natural tiltmeter to determine deformation, could also be used at Ruapehu.

Geodetic levelling and EDM determine elevation and distance between two points respectively (Figure 3.3) and have been used in the past. Current deformation is only measured using continuous global positioning system (cGPS) measurements. At Ruapehu there are seven cGPS sites (Figure 3.1) that record their position once every one or 30 seconds

(GeoNet website, 2009) and send it to the Wairakei Observatory as real-time data. When all the sites are combined, millimetre accuracy is possible (GeoNet website, 2009), which provides high quality real-time deformation data.

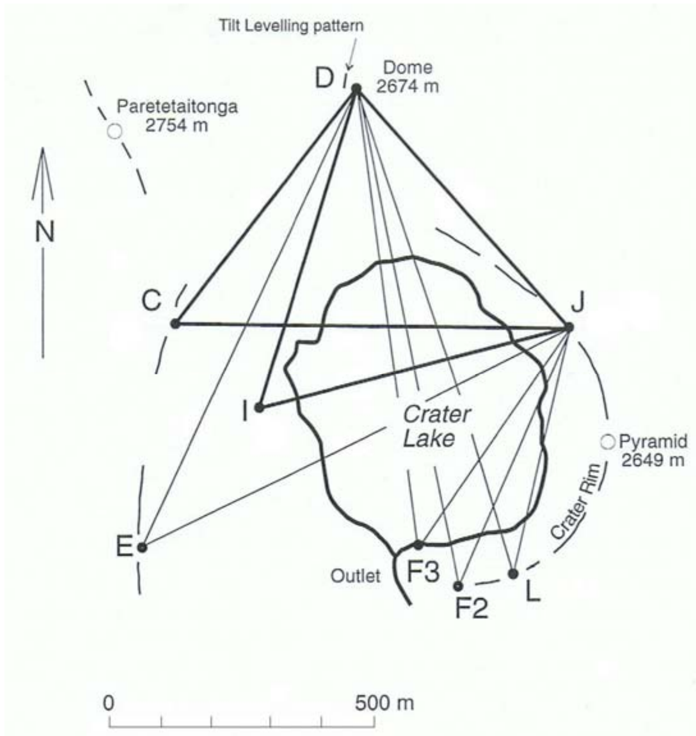


Figure 3.3: Sketch map showing the peg locations for EDM. Line IJ is used here which has a base distance of 600 m (from Scott *et al.*, 1998).

3.5. Gas Emissions

Certain volcanic gases may show early signs of changing conditions below the vent. As magma rises to shallow levels it depressurises and the gas escapes into the atmosphere. If the type and amount of gas is measured, it may provide warning of an impending eruption.

The most common gases are monitored at Ruapehu are sulfur dioxide (SO_2), carbon dioxide (CO_2) and hydrogen sulfide (H_2S). The amount of SO_2 is measured with an optical correlation spectrometer (COSPEC) by flying under the plume and measuring the amount of ultraviolet light that is absorbed by SO_2. A new, low cost ultraviolet correlation spectrometer (FLYSPEC) has been developed to replace COSPEC (Horton *et al.*, 2006), and has been used at Ruapehu routinely since mid-2008. The amount of CO_2 is measured with a small infrared analyser (LICOR) which is flown through the plume several times. This method is called plume contouring (Gerlach *et al.*, 1997), where the instruments are flown through the plume at different altitudes to get a measurement of the whole plume (GeoNet website, 2009).

These data are not real-time. Measurements are taken monthly, or more frequently during periods of increased unrest, and have only been carried out at Ruapehu consistently since 2003, with some COSPEC measurements taken during the 1995-1996 eruptions. To obtain real-time data a mini-DOAS system (miniature differential optical absorption spectroscopy) has been implemented at White Island, but it is more difficult to install for Ruapehu (Scott and Travers, 2009).

Chapter Four – Poás Volcano

Poás volcano is within a Quaternary volcanic arc (Rowe *et al.*, 1992a) approximately 30 km NW of San José, in the Cordillera Central of Costa Rica (Figure 4.1 A). The volcanism in this arc is associated with the subduction of the Cocos plate beneath the Caribbean plate at a rate of ~85 mm/y (DeMets, 2001). Poás is a basaltic-andesite stratovolcano (Martínez *et al.*, 2000) sitting atop a massive volcanic pile of welded and non-welded ignimbrites and lava flows, the youngest of which has been dated to 0.98 Ma (Stevenson, 1992). The summit area consists of two large nested calderas (Prosser and Carr, 1987) within which is the highly eroded Von Frantzius cone; the younger Botos cone to the south, which contains a fresh water lake; and the main crater in the centre, the site of all historic activity (Prosser and Carr, 1987; Stevenson, 1992) (Figure 4.1 B).

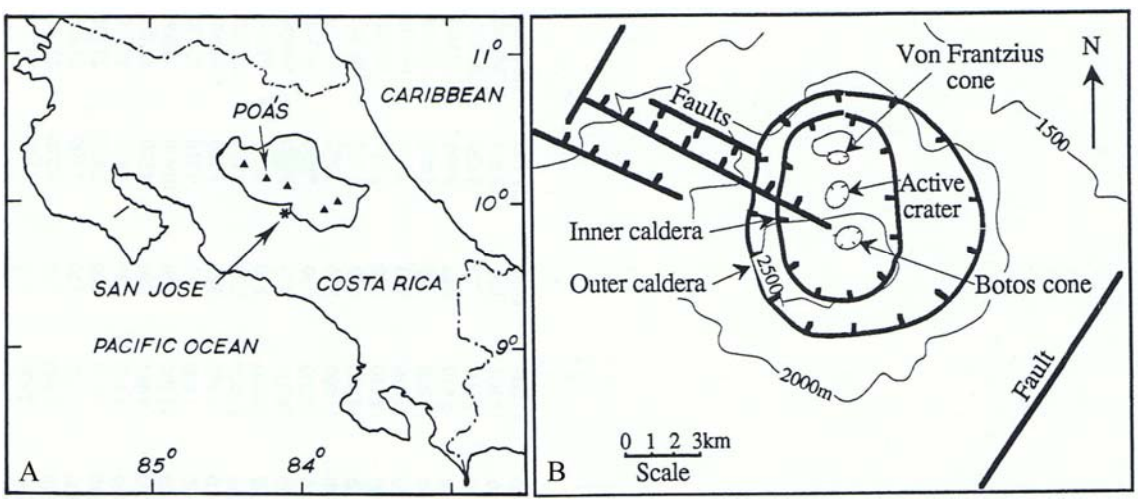


Figure 4.1: (A) Location map of Poás volcano, central outlined area is the Cordillera Central; (B) Structure of the summit region at Poás (adapted from Rowe *et al.*, 1992a; Stevenson, 1992).

4.1. Eruptive History

The main crater has a diameter of 800 m and encloses two smaller nested craters (Prosser and Carr, 1987), the northern one containing a hot, acidic crater lake (Laguna Caliente), and a pyroclastic cone (Rowe *et al.*, 1992a). The lake, which has been present since 1965 to a greater or lesser extent, and the pyroclastic cone have been the sites of historic activity, with numerous phreatic and geyser-like eruptions (Stevenson, 1992) and rare phreatomagmatic eruptions (Rowe *et al.*, 1992a).

The earliest reports of volcanic activity were for the period 1826-1828, when phreatic explosions were reported (Stevenson, 1992). The largest recorded eruption was on 25 January 1910, when most of the lake water was erupted and an ash column rose to 8 km above the summit (Martínez *et al.*, 2000). Phreatomagmatic activity commenced in 1952, which ejected all the lake water and produced a pyroclastic cone (Martínez *et al.*, 2000). This activity ceased in 1953 and the lake had returned to its previous level by 1965.

Between 1965 and 1980, intermittent, vigorous episodes of phreatic activity occurred (Rowe *et al.*, 1992a) with column heights from several metres to 2 km, and larger phreatic eruptions in 1978 which ejected sulfur-encrusted blocks (Martínez *et al.*, 2000). This 1978 eruption suggests a layer of molten sulfur exists at the bottom of the crater lake (Bennett and Raccichini, 1978), similar to that at the bottom of Crater Lake, Ruapehu.

In January 1981, fumaroles on the pyroclastic cone reached ~900 °C (Rowe *et al.*, 1992a) and gas columns rose up to 2 km high. At this time phreatic activity within the lake ceased (Martínez *et al.*, 2000). Fumarolic temperatures gradually decreased and were less than 100 °C in 1989. Over this period the lake level decreased and temperature increased, until April 1989, when the lake completely disappeared (Martínez *et al.*, 2000). This disappearance was followed by several weeks of phreatic activity, which led to dry ash eruptions and vigorous fumarolic activity. During this time sulfur pools and volcanoes were seen on the lake bottom (Martínez *et al.*, 2000). The lake reformed during the wet season of 1989 but dried up again in April 1990 (Rowe *et al.*, 1992a), resulting in more dry ash eruptions.

The lake began to refill until a series of eruptions in 1994 ejected water, lake sediments, andesite blocks and ash over large areas. Only minor fumarolic activity occurred at Poás until 24 March 2006, when small phreatic eruptions occurred, which ejected water, gas and sediments through the crater lake (Smithsonian Institution, 2009a). Phreatic eruptions also occurred later in the year as well as in January 2008 and 2009 (Smithsonian Institution, 2009a).

4.2. Monitoring

Monitoring at Poás began in the late 1970s with seismic and temperature recordings, and since then more techniques have been included such as: lake water chemistry; ground deformation; microgravity (Figure 4.2 and Table C.1). Monitoring has been carried out by staff of the Universidad Nacional de Heredia, Costa Rica and the Observatori Vulcanológico y Sismológico de Costa Rica (OVSICORI), the equivalent of GNS Science. Visual observations can be made daily as the area is a national park and is open to visitors. There are also webcams pointed towards the crater lake. Rainfall is also monitored, as lake temperature, chemistry and level can change during wet and dry seasons.

4.2.1. Lake Water Temperature

The water temperature of the active crater lake has been measured at approximately monthly intervals since 1978 (Rowe *et al.*, 1992b). Sharp fluctuations are usually seen during periods of increased phreatic activity such as in 1978 and 1979 (Rowe *et al.*, 1992b). During less active periods the temperature displays seasonal variations (Rowe *et al.*, 1992b), with low temperatures in the wet season (May-December) and high temperatures in the dry season (January-May) (Martínez *et al.*, 2000). The highest temperature, 94 °C, was recorded in July 1990 (Barquero *et al.*, 2005), before the lake disappeared for the second time in two years due to increased evaporation (Rowe *et al.*, 1992a).

4.2.2. Lake Water Chemistry

Water samples used to determine chemistry of the lake water have also been taken monthly since 1978 (Barquero *et al.*, 2005). The main constituents analysed are magnesium, chloride, fluoride, sulfate (Rowe *et al.*, 1992a; Martínez *et al.*, 2000; Barquero *et al.*, 2005) and the Mg/Cl, SO_4/Cl and F/Cl ratios (Rowe *et al.*, 1992a; Rymer *et al.*, 2000). Rowe *et al.* (1992a) indicated that these ‘classical’ parameters gave little indication of impending eruptive activity, and were probably influenced by enhanced release of HCl vapour, due to the increase in lake temperature. They suggested that variations in polythionic acid ($H_2S_xO_6$, x = 4-6) concentration gave better indications of renewed phreatic activity in June 1987.

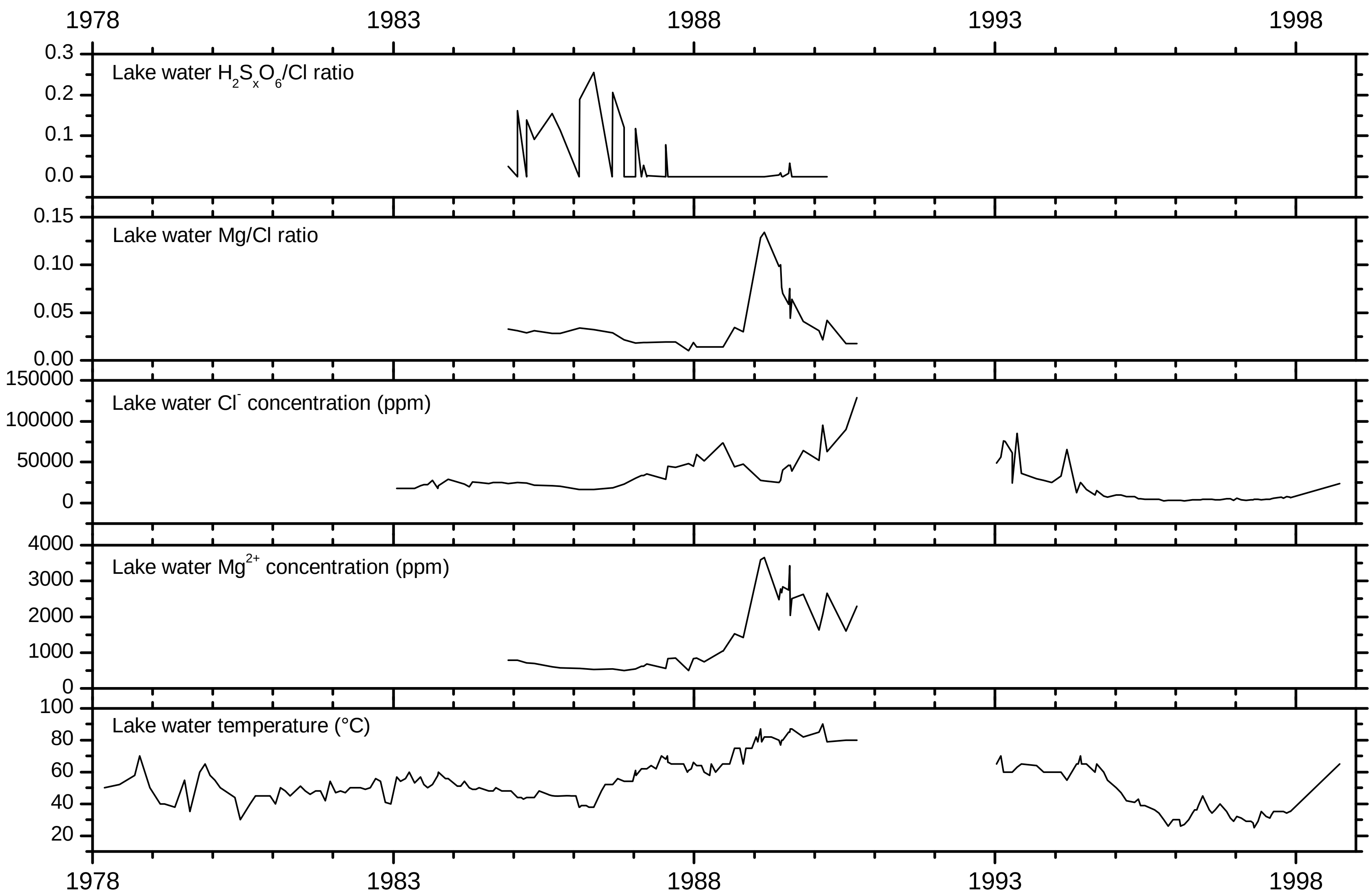


Figure 4.2: Lake water chemistry and temperature at Poás from 1978 to 1988.

Polythionic acids can be found in places where H_2S and SO_2 gases react in aqueous environments (Takano and Watanuki, 1990), i.e. volcanic crater lakes. These acids respond sensitively to shifts in H_2S and SO_2 emissions due to the variations in volcanic activity (Takano and Watanuki, 1990). When gas of high SO_2/H_2S ratio enters the lake, the polythionic acids break down and are only just above detection limits (Rowe *et al.*, 1992a), and with high H_2S emissions, polythionic acid concentrations will increase (Takano and Watanuki, 1990).

At Poás, increased seismic activity occurred in early 1986 as a result of hydrofacturing or magma ascent (Rowe *et al.*, 1992b). At this time polythionic acid concentrations increased as rising SO_2-rich gas was converted to H_2S (Rowe *et al.*, 1992a). Increasing SO_2 emission could not be converted to H_2S, which resulted in the break down of polythionic acids, which led to low concentrations, three months before renewed phreatic activity (Rowe *et al.*, 1992a).

These chemical parameters may be unreliable where there are large fluctuations of the lake level, as certain chemical parameters may become concentrated or diluted. For the period 1983-1989, Stevenson (1992) overcame this problem by converting magnesium and chloride concentrations to total amounts within the current lake volume. This has not been necessary recently as the lake level has remained relatively stable. Large increases in rainfall and lake temperature may also concentrate or dilute chemical parameters.

4.2.3. Seismicity

Seismic data has been recorded from the summit area of Poás since 1980 (Rowe *et al.*, 1992b). The seismicity can be categorised as: (1) type-A events (high frequency, >3 Hz); (2) type-B events (low frequency, <3 Hz); and tremor (2-3 Hz), (Rowe *et al.*, 1992b; Martínez *et al.*, 2000; Rymer *et al.*, 2000).

Type-A events have been erratic in their occurrence with notable peaks in 1980 and 1990 (Rymer *et al.*, 2000), when >600 events occurred, compared with the normal background of <200 events. The source of these events is thought to be hydrofracturing of the brittle portions of the magma body accompanied by the release of magmatic volatiles (Rymer *et al.*, 2000). This is evident by the increase in fumarole temperatures on the dome (Martínez *et al.*, 2000; Rymer *et al.*, 2000).

Type-B events are the most common at Poás with a background level of ~50 events per day (Rowe *et al.*, 1992b). Epicentre locations of 100 events in 1989 showed they were generated directly below the crater, at a depth of less than 600 m (Rowe *et al.*, 1992b; Rymer *et al.*, 2000). The source for these events is believed to be the movement of high temperature fluid-gas mixtures through the hydrothermal system (Rowe *et al.*, 1992b; Rymer *et al.*, 2000). Evidence for this can be seen between 1989 and 1993, when the number of type-B events increased and the lake temperature also increased (Rowe *et al.*, 1992b).

The tremor that has been recorded at Poás can be divided into volcanic and harmonic tremor. Volcanic tremor has a similar source to type-B events and is also thought to result from degassing magma. The decrease in tremor and fumarolic temperature between 1981 and 1985 supports this (Rowe *et al.*, 1992b). Low amplitude harmonic tremor is poorly understood at Poás but is thought to result from the ascent of magma (Rowe *et al.*, 1992b).

4.2.4. Microgravity

Microgravity can be used to determine increases in subsurface density due to magmatic intrusions (Rymer, 1995) and has been used at Poás since 1979 (Rymer and Brown, 1989). Data have been collected up to three times a year since 1985, with the largest increases at the crater bottom sites between 1985 and 1989 (Rymer *et al.*, 2000). During this period lake level was decreasing, and one would expect microgravity to decrease as well; however, it increased. Rymer *et al.* (2000) concluded that magma had intruded below the lake, causing the increase in the microgravity trend and the associated thermal activity in the lake. After the 1989 eruptions, microgravity decreased, indicating the magma level had dropped (Rymer *et al.*, 2000). Between 1992 and 1993 microgravity increased but was not followed by eruptions and was associated with the rise of the water table and recovery of the hydrothermal system after the eruptions (Rymer *et al.*, 2000). Rymer and Brown (1989) suggest this technique could be valuable in predicting future eruptions at Poás.

4.2.5. Ground Deformation

Ground deformation was measured in 1983, 1988, 1989 and between 1991 and 1994 (Rymer *et al.*, 2000). No systematic trend was found and the deformation was only minor (± 5 cm). Rymer *et al.* (2000) associates the deformation to local changes in the hydrothermal system and suggests deformation is not a good primary monitoring tool at Poás.

Chapter Five – Ruapehu Monitoring Data

Volcanic monitoring data from Ruapehu from 1960 to 2008 are summarised in Figures 5.1, 5.3 and 5.4 and Table B.1. Figure 5.2 shows a more detailed view of Crater Lake water chemistry and temperature between 1966 and 1976.

Eruptive activity follows a cyclic pattern, with larger eruptions (magnitude 3-5) occurring between 1968-1978 and 1995-1996, and smaller eruptions (magnitude 1-2) occurring between two these periods. The eruption style is also cyclic, with mainly phreatomagmatic eruptions occurring between 1968 and 1978, while in the 1995-1996 period there were some magmatic eruptions as well as phreatomagmatic. These patterns may be indications of the volcanic processes at Ruapehu.

The water temperature of Crater Lake also displays a cyclic pattern and generally ranges from 15 to 40 °C, with a minimum of 9 °C reached on 14 November 1988 and a maximum of 69 °C on 8 November 1998. It can be seen that any magnitude eruption can occur when the water temperature is high (e.g. 1971 and 1975 eruptions) or low (e.g. 1988 and 2007 eruptions).

Lake water chemistry data display different patterns throughout the record, with the Mg/Cl ratio having the most pronounced pattern (Figure 5.1). Between 1967 and 1975 there were four periods, lasting between 6-15 months, where the Mg/Cl ratio was constant, and each period ended with a significant eruption (magnitude 3-5) (Figure 5.2). Constant magnesium concentrations also define these four periods. After 1978 a pattern of decreasing Mg/Cl ratio, with some periods of rapid increase, persisted until early 1995, when another rapid increase occurred before major phreatomagmatic and magmatic eruptions. The Mg/Cl ratio peaked in 2001 and was decreasing to a higher background level than it was pre-1995 until it increased immediately prior to the 2007 eruption.

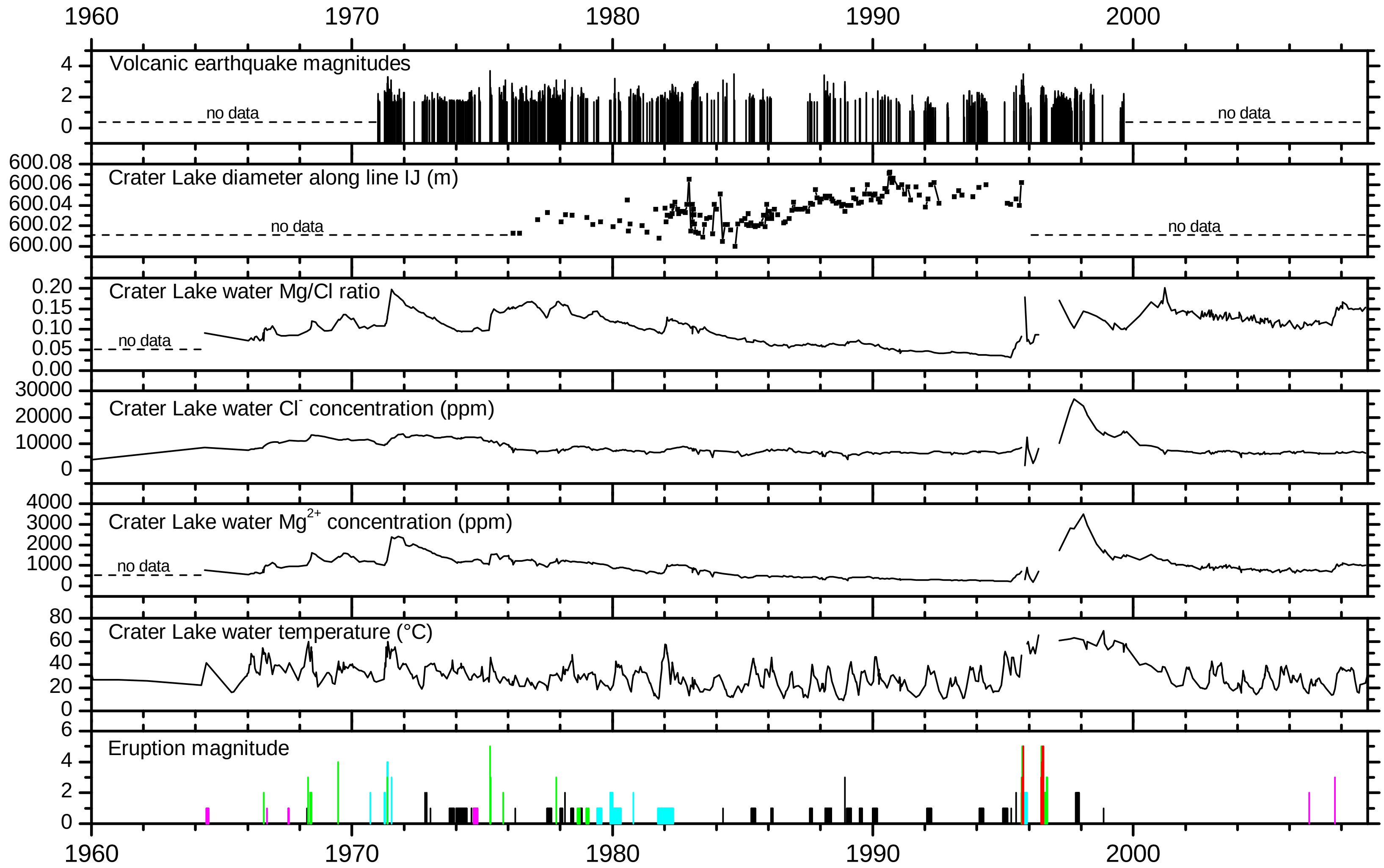


Figure 5.1: Graph showing seismicity, water chemistry and temperature and eruption magnitude at Ruapehu from 1960 to 2008. The eruption magnitude is a semi-quantitative estimate based on observed effects (Table A.2). Colours represent eruption style and are: (pink) hydrothermal; (black) phreatic; (blue) phreatic/phreatomagmatic; (green) phreatomagmatic; and (red) magmatic. 'No Data' indicates extended periods of no data.

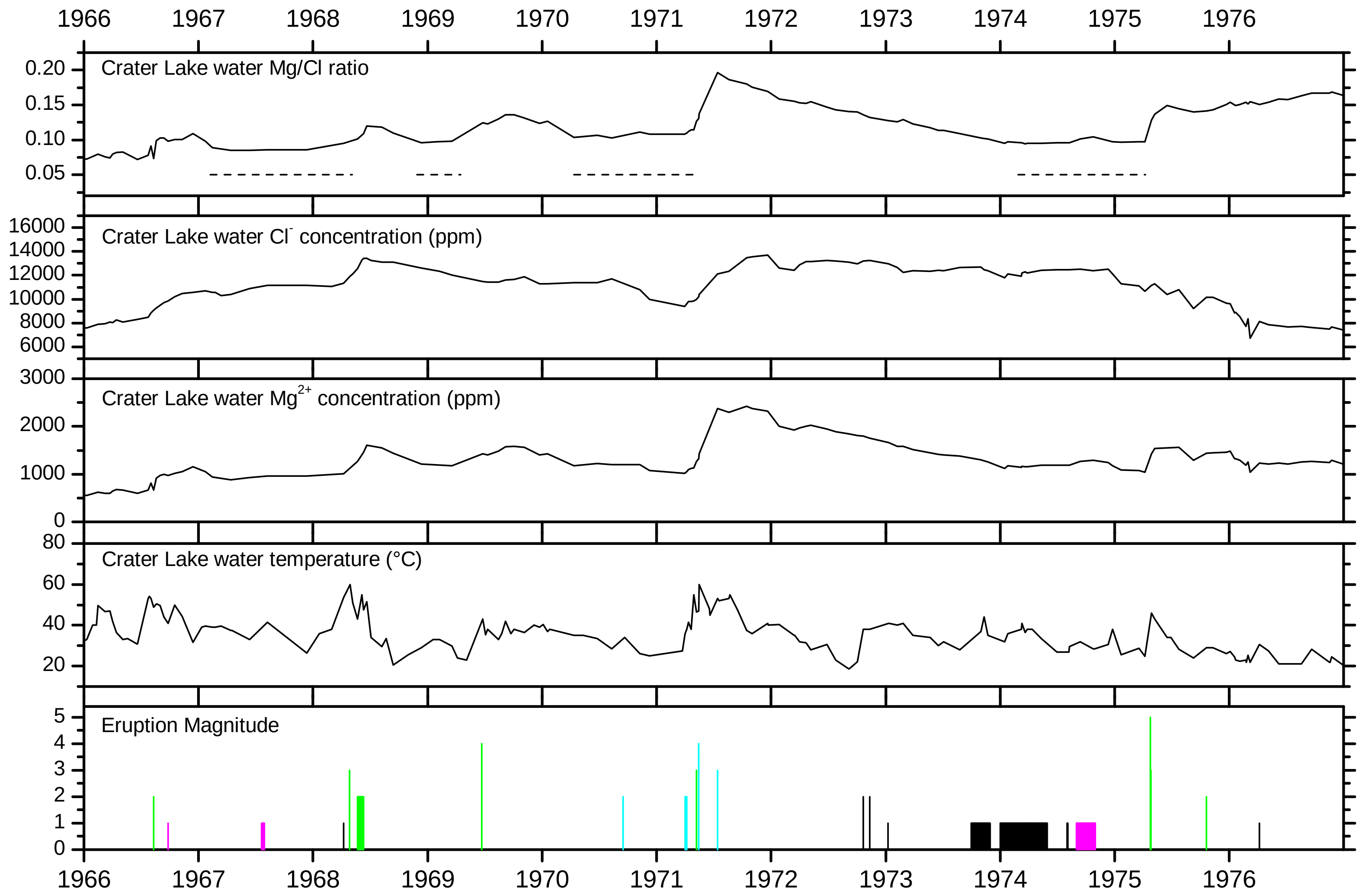


Figure 5.2: Graph showing water chemistry and temperature and eruption magnitude at Ruapehu from 1966 to 1976. Horizontal dashed lines represent periods where the Mg/Cl ratio was constant prior to major eruptions. The eruption magnitude is a semi-quantitative estimate based on observed effects (Table A.2). Colours represent eruption style and are: (pink) hydrothermal; (black) phreatic; (blue) phreatic/phreatomagmatic; and (green) phreatomagmatic.

EDM of ground deformation across Crater Lake between 1976 and 1996 show that the crater diameter either increased or decreased before major eruptions (Figure 5.1). The crater diameter increased by 20 mm in the two years preceding the magnitude three eruption in 1977, whereas before a magnitude three eruption in 1988, the diameter decreased by 8 mm. The diameter also decreased preceding an eruption in June 1995. During 1980-1992, when there were many magnitude one eruptions, the crater diameter was generally increasing.

Three forms of seismic data are presented here; volcanic earthquake magnitudes (Figure 5.1), seismic amplitude from Dome Shelter and RSAM from the Far West T-bar (Figure 5.3). Volcanic earthquakes result from magmatic processes taking place within and below the vent, and can indicate movement of magma. At Ruapehu large numbers of these earthquakes tend to occur during or after eruptions. Both the seismic amplitude and RSAM data show the amplitudes of seismic activity at Ruapehu, but in slightly different ways, and therefore cannot be directly compared to each other. Comparison between RSAM and eruptive activity is difficult as there have only been two eruptions in the nine year period since this data started to be collected. RSAM data in Figure 5.3 have been filtered to 1-3 Hz and smoothed to 144 points using the adjacent-averaging method.

High gas emissions from volcanoes may be caused by increases in magmatic activity and eruptions. At Ruapehu there have only been two eruptions since consistent gas monitoring started in 2003 (Figure 5.4). Within this six year period there have not been large increases in CO_2 and SO_2 before eruptions, only afterwards. Only CO_2 shows increases and decreases in emission as a result of increasing and decreasing lake temperatures.

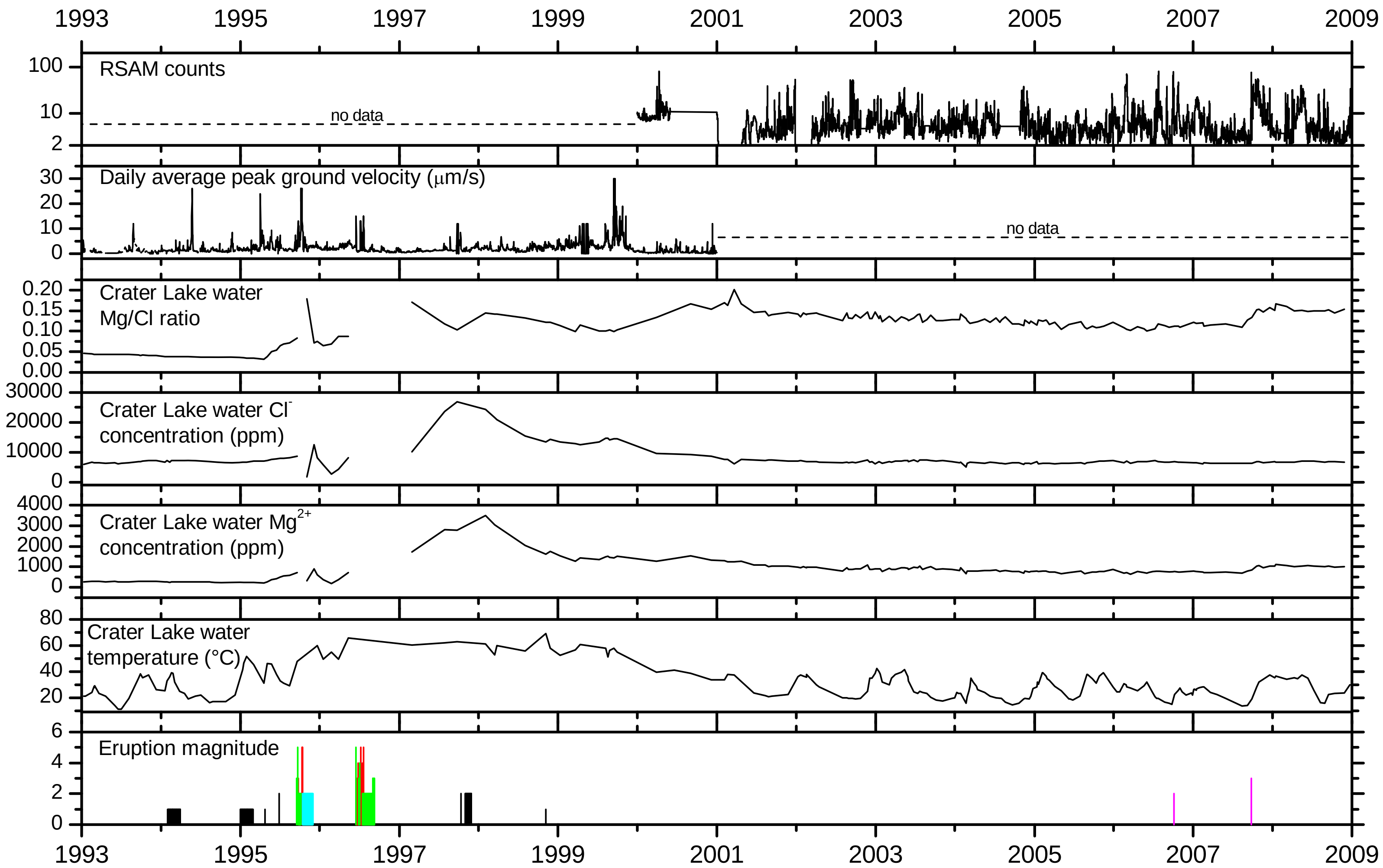


Figure 5.3: Graph showing seismicity, water chemistry and temperature and eruption magnitude at Ruapehu from 1993 to 2008. The eruption magnitude is a semi-quantitative estimate based on observed effects (Table A.2). Colours represent eruption style and are: (pink) hydrothermal; (black) phreatic; (blue) phreatic/phreatomagmatic; (green) phreatomagmatic; and (red) magmatic. 'No Data' indicates extended periods of no data.

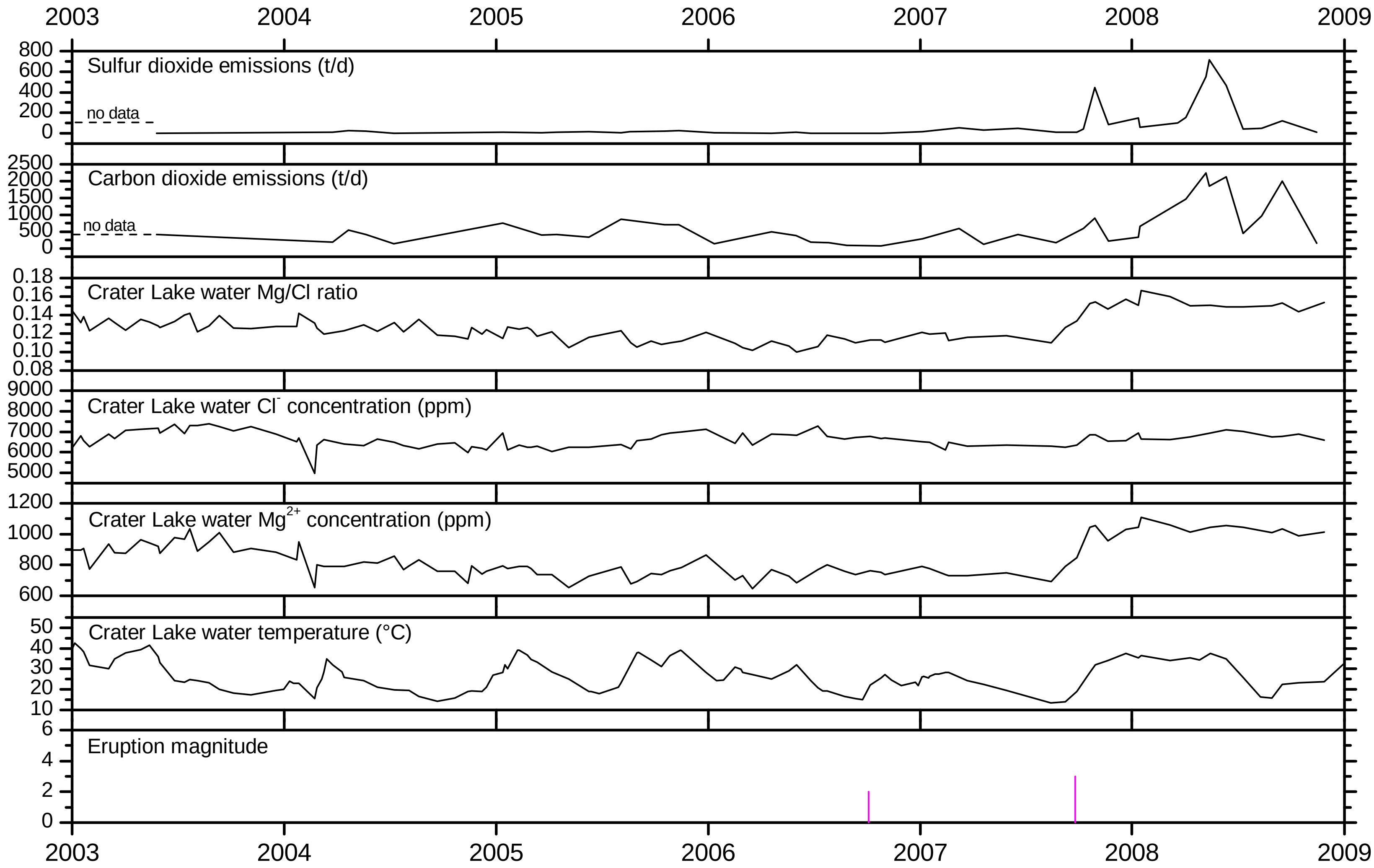


Figure 5.4: Graph showing gas emissions, water chemistry and temperature and magnitude of hydrothermal eruptions at Ruapehu from 2003 to 2008. The eruption magnitude is a semi-quantitative estimate based on observed effects (Table A.2). 'No Data' indicates extended periods of no data.

Chapter Six – Discussion

The cyclic pattern of lake temperature at Crater Lake is controlled by a layer of liquid sulfur on the bottom of the lake. The highly temperature dependent viscosity of liquid sulfur allows heat and gas to pass through at certain times, while at other times the vent is closed. This results in heating cycles which generally last 2-4 months when the vent is open and cooling cycles which last 6-15 months when the vent is closed. However sometimes rapid heating and cooling occurs. For example, in 1995 there were two heating and cooling cycles. One would expect the majority of eruptions to occur after cooling cycles when the vent is closed, allowing pressure to build, but just over half of the magnitude two or larger eruptions have occurred when the lake temperature was high. Therefore, lake temperature alone cannot be used to predict volcanic eruptions, although it can be used to provide insight into whether the vent is open or closed.

By far the most useful parameters for predicting future eruptions are the chemical constituents: magnesium, chloride and the Mg/Cl ratio, although these data do have shortfalls. Between 1967 and 1975, all of the major eruptions (magnitude two and above) were preceded by extended periods of 6-15 months where the Mg/Cl ratio was constant (Figure 5.2). Also during these periods, chloride and magnesium concentrations and temperature were constant or decreasing. These trends indicate that the vent was closed and no heat or chemical components were entering the lake (Giggenbach, 1983). This would then allow the pressure to build up over time, in these cases for six months or more, until a critical point when an eruption occurred. After the eruptions, the magnesium, chloride and temperature values increased, indicating the vent was open and fumarolic activity and water-rock interactions had resumed.

This pattern has not occurred since 1975, and therefore may only be related to extended periods of phreatomagmatic activity, as was seen between 1967 and 1975. In the future, if the Mg/Cl ratio remains constant and the lake temperature is constant or decreasing for six months or more it is highly probably an eruption will occur within the following 12 months (Giggenbach, 1983), and increased monitoring should take place.

A different type of pattern occurred before the major phreatomagmatic and magmatic eruptions of the 1995-1996 eruptive period. Immediately before the 1995 eruption, both the magnesium and the Mg/Cl ratio values increased dramatically, with only a minor increase in chloride. This indicates that magma had made contact with water of the hydrothermal system below the lake and was interacting with lake water. However, deformation data did not show any major changes related to the intrusion until four months later. This could be because the intrusion was not deep enough to deform the crater, but was still able to provide fluids to the lake, and it was not until the magma moved higher up that ground deformation occurred. The unusual aspect of the increase in magnesium and the Mg/Cl ratio is that the trend occurred over two cooling phases (Christenson, 2000). This is a result of the top of the intrusion being quenched and blocking heat and gas flow into the lake, while still allowing rock dissolution to continue (Christenson, 2000). This trend had never occurred previously or since 1995. It is inferred that this trend only occurs before major phreatomagmatic and magmatic eruptions, as these eruptions result from large volume magmatic intrusions, compared with small volumes prior to small eruptions. If a sustained increase in magnesium concentration and the Mg/Cl ratio occurs over successive cooling phases and is increasing for approximately one year, there is a high probability of a major eruption.

There are some shortfalls in relying on chemistry data for predicting eruptions. Between December 1981 and January 1982, magma intruded below the lake, as indicated by the increase in magnesium concentration. This resulted in a rapid increase in the Mg/Cl ratio and the highest lake temperature in 10 years. However, only minor (magnitude one) intermittent phreatic and phreatomagmatic eruptions occurred, where one would expect larger magnitude eruptions. A similar increase in the Mg/Cl ratio occurred in 1977, but over four months instead of two. This resulted in a magnitude three phreatomagmatic eruption. Another similar increase occurred in 2007, this time one month before and one month after a magnitude three hydrothermal eruption. These three examples illustrate differences in outcome after similar initial conditions, which make reliable prediction of eruptions difficult.

Volcanic earthquake magnitude data from 1971 to 1999 does not provide any useful precursor information as there is no overall pattern before eruptions. The largest magnitude volcanic earthquakes occurred during or after eruptions, but did not necessarily occur during large magnitude eruptions. The highest frequency of these earthquakes tends to occur during or after eruptions. There also appears to be very little correlation with other data sets, with large magnitude and closely grouped volcanic earthquakes occurring during both high and low water temperatures and when the Mg/Cl ratio is increasing or decreasing. This suggests that some volcanic earthquakes originate from another source than under Crater Lake (Latter, 1998), as they would not be expected to occur when the vent is open, indicated by the high Mg/Cl ratio and high lake temperature.

Seismic amplitude data from the Dome Shelter site between 1993 and 2001, again, does not display any consistent precursor activity before major eruptions. In early 1995 the seismic amplitude peaked above 20 µm/s just two weeks before the Mg/Cl ratio started to increase, indicating the intrusion of magma below the vent. This intrusion led to major phreatomagmatic and magmatic eruptions. After the 1995 eruptions, seismicity returned to background levels and gave no indication of the large eruptions in 1996. During late 1999 the amplitude peaked above 20 µm/s, then dropped to 10 µm/s for one month, which coincided with an increase in the Mg/Cl ratio, indicating a magmatic intrusion. However, no eruption resulted from these changes and the seismicity returned to background levels. This again shows that increases in seismicity can occur without eruptions and could lead to false predictions.

Defining any precursor activity using the RSAM data from the Far West T-bar site is difficult as there have only been two eruptions in the nine year period. Before the 2006 eruption there was no unusual precursor activity, and earlier in the year there were two occasions when the seismicity was higher, yet no eruption followed these. Before the 2007 eruption the seismicity was at background levels and did not indicate a future eruption. As a result of the eruption the seismicity increased, but this is of no help in predicting eruptions. Prior to this eruption there was a small increase in the magnesium concentration, which could have indicated a magmatic intrusion, although similar increases had occurred in the previous five years. This eruption originated from the northern vent (Brad Scott, *pers. comm.,* 2009), which may operate under slightly different conditions to the main vent.

The minor and ambiguous nature of seismicity before eruptions could infer the vent is open and magma can intrude without rock fracturing and preventing the build up of stress (Bryan and Sherburn, 1999). This is consistent with the majority of eruptions occurring when the lake temperature is high. Even when the vent is inferred to be closed (i.e. low lake temperature), seismicity has not built up for long periods before eruptions (e.g. 2007 eruption, Figure 5.3), as one would expect. However, this may be a function of the eruption magnitude, as many ‘closed vent’ eruptions are magnitude three or less, which do not result from magmatic intrusions and therefore have less associated seismicity.

The lack of seismicity could also be due to the small amount of magma involved in the eruptions (Bryan and Sherburn, 1999). The 1995-1996 eruptions were the largest to occur recently and these involved a magmatic volume of 0.05 km^3 (Nakagawa *et al.*, 1999). Thus, most other eruptions would involve smaller amounts of magma. This small amount may be able to pass through the conduit relatively unimpeded and result in limited seismic activity.

Increased seismicity without eruption may be a result of intrusions deep below the summit of Ruapehu or the filling of shallow magma chambers. This can be determined from the source depth of the seismicity; however, this is sometimes difficult (Latter, 1998; Sherburn *et al.*, 1999).

Gas emissions show a cyclic pattern, with CO_2 more pronounced than SO_2 (Figure 5.4). The cyclicity could be the result of the build up of gas at the base of the lake, and subsequent release during lake heating cycles (Werner *et al.*, 2006) when the vent becomes open. Sometimes the peak CO_2 emission lags behind the peak in lake temperature, which indicates that the magma and the source of gas are at a significant depth and take time to travel to the surface (Werner *et al.*, 2006). This time delay may also apply to chemical changes and may be used to determine the approximate depth to the magma body and its change in depth over time.

There were no anomalous gas measurements before the 2006 and 2007 eruptions, possibly because these eruptions were hydrothermal and probably originated at the bottom of the lake, which would not affect the hydrothermal system below. Also, these eruptions occurred when the lake temperature was low, indicating the vent was closed, and may have prevented gas from venting until after the eruption.

In 2008, there were large peaks of both SO_2 and CO_2 six months after the 2007 eruption. These peaks corresponded well with the RSAM data and may have been caused when a fracturing event in the hydrothermal system allowed gas to vent under an open vent configuration (indicated by the sustained high lake temperature), as a result of reconfiguration of the system after the eruption. These peaks are very anomalous compared with the rest of the record (Figure 5.4) and may have prompted concern for an impending eruption; however, this did not occur. As the gas record becomes longer and more detailed, and more eruptions occur, a stronger correlation between eruptions and other data sets may become apparent.

Ground deformation may not be useful for predicting eruptions as the crater diameter increases or decreases before eruptions. Prior to the 1995 phreatomagmatic eruption, a large increase in crater diameter occurred only a few weeks before the eruption, as a result of a magmatic intrusion. This deformation was a very short term response, as magnesium and chloride concentrations had already changed. Prior to another phreatomagmatic eruption in 1977, the crater diameter decreased, when one would expect it to increase as magma intruded. Before the 1988 phreatic eruption, the crater diameter decreased, and paralleled the decrease in water temperature. Thus deformation in this case was probably caused by a change in the hydrothermal system, and not the deflation as a result of descending magma. It may be difficult to use ground deformation data to determine volcanic processes, as two different mechanisms can cause the observed changes.

When comparing water chemistry and temperature data it becomes apparent that eruptions occur at average values (Figure 6.1), however, eruptions can occur at other times, which makes the prediction of eruptions problematic.

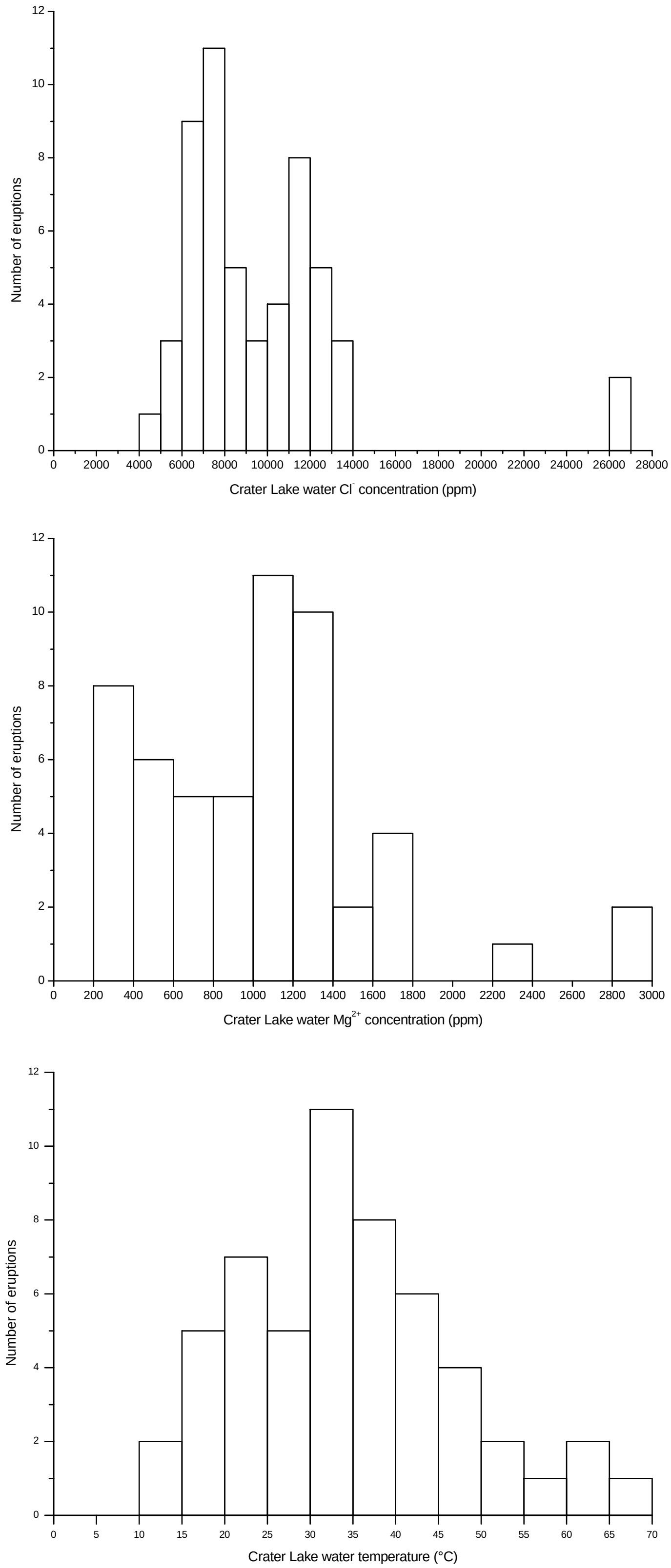


Figure 6.1: Graphs showing the number of eruptions that occur at different temperature and chemical concentrations.

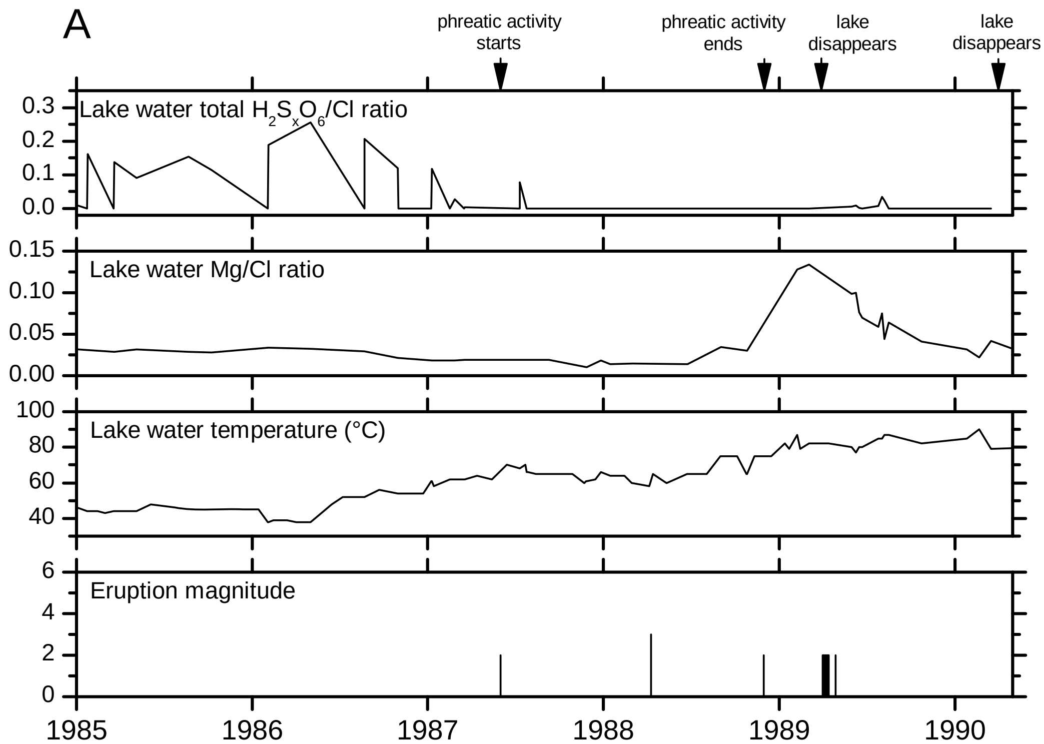
6.1. Comparison with Poás

Both Ruapehu and Poás volcanoes contain crater lakes that operate in very similar ways, with heat and gases passing from the hydrothermal system to the lakes.

The non cyclic pattern of lake temperature at Poás (Figure 4.2) indicates that the layer of sulfur on the bottom of the lake remains liquid, giving rise to an open vent. In addition, large influxes of heat and gas can pass into the lake, causing large fluctuations in temperature, lake levels and chemical concentrations. The lake at Poás is also strongly influenced by rainfall, with large quantities entering the lake during the wet season.

The magnitude and frequency of eruptions at the two volcanoes is very different. At Poás, a large number of phreatic eruptions occur with only rare phreatomagmatic eruptions, whereas Ruapehu has frequent phreatic and phreatomagmatic eruptions. Like Ruapehu, eruptions at Poás can occur at anytime, making prediction difficult.

A study by Rowe *et al.* (1992a) concluded that 'classical' chemical parameters such as magnesium and chloride concentrations and the Mg/Cl ratio provided no information about impending eruptions. The study also concluded that polythionic acid concentrations provided more information, and clear patterns appeared before eruptive periods (Figure 6.2 A). Polythionic acid concentrations have also been studied at Ruapehu between 1968 and 1988 by Takano *et al.* (1994) (Figure 6.2 B), and provide the only similarity between the two volcanoes. At both volcanoes the acid concentrations decreased to almost zero before or just after the onset of eruptive activity. In some cases this occurred three months before an eruption (e.g. 1978 at Poás and 1971 at Ruapehu). This decrease is the result of an increase in the SO_2/H_2S ratio of the gas entering the lakes. The opposite trend can be seen in SO_2 emissions (i.e. low emissions before eruptions, and high during an eruption), so the two data sets can be combined to provide a possible prediction on impending eruptions. However, the trend does not always occur before an eruption; for example, the 1988 eruption at Ruapehu had no precursors.



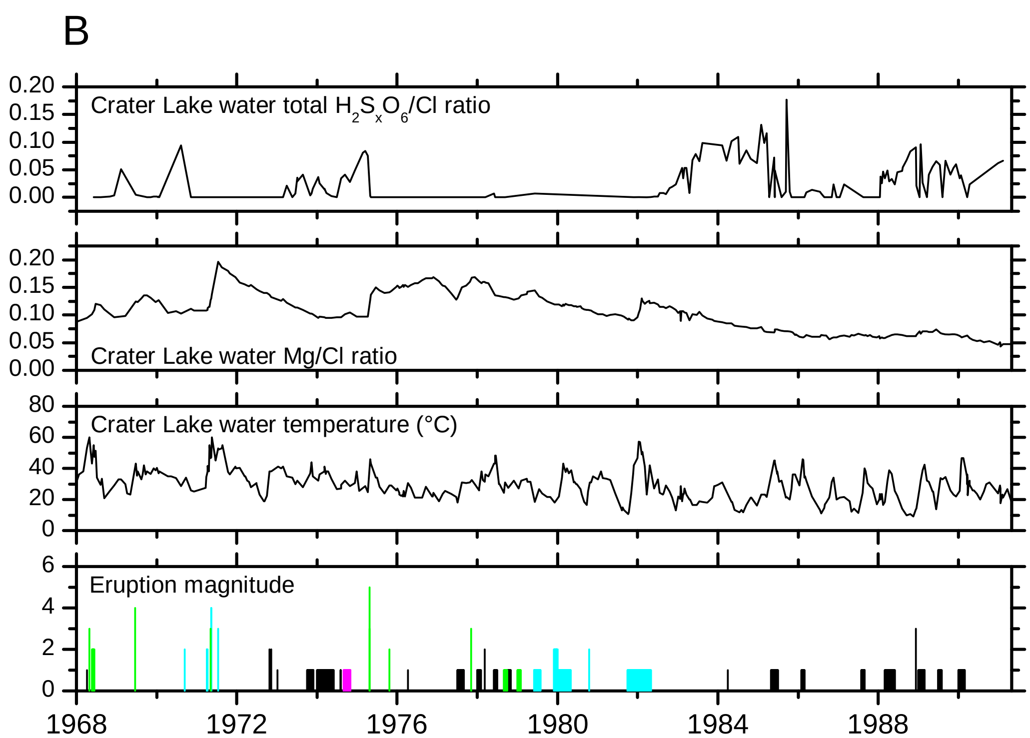


Figure 6.2: (A) Graph showing $H_2S_xO_6$/Cl and Mg/Cl ratios, water temperature and eruption magnitude at Poás from 1985 to 1990. (B) Graph showing $H_2S_xO_6$/Cl and Mg/Cl ratios, water temperature and eruption magnitude at Ruapehu from 1968 to 1990. Colours represent eruption style and are: (pink) hydrothermal; (black) phreatic; (blue) phreatic/phreatomagmatic; (green) phreatomagmatic; and (red) magmatic.

Chapter Seven – Conclusions and Recommendations

7.1. Key Conclusions

The impacts from a volcanic eruption at Ruapehu would affect a large number of people and will spread over a large area. By being able to predict eruptions, these effects could be minimised; however, this study did not find any consistent patterns in the monitored parameters that could be unequivocally used to predict eruptions. It was found that eruptions have a higher probability of occurring when monitored parameters are at average values; however, eruptions can occur at anytime, which may lead to false predictions.

Crater Lake water chemistry, especially magnesium and chloride concentrations and the Mg/Cl ratio, show the most promise, but the patterns are inconsistent. Between 1967 and 1975, all large eruptions were preceded by periods of 6-15 months when the Mg/Cl ratio was constant. It is implied that the vent was closed, and pressure was building up until a critical point was reached when an eruption occurred. This pattern may be used for reliable prediction, but it has not occurred since 1975 and is probably only related to extended periods of phreatic and phreatomagmatic eruptions. Six months prior to major phreatomagmatic eruptions in 1995, the Mg/Cl ratio started to increase and continued at a rapid rate over two cooling cycles, indicating a possible magmatic intrusion. This pattern may be used for prediction, but it has not occurred since 1995 and may only be related to major phreatomagmatic and magmatic eruptions. In the future these two patterns could be used to predict eruptions as well as the style of activity.

Polythionic acid concentrations may also be used to predict eruptions. Sharp decreases in concentration have occurred prior to eruptions at Ruapehu (1969, 1971, 1975, and 1988) and Poás (1987) and sometimes gives up to three months warning. However, this pattern can occur during eruptions and sometimes not all.

Despite all the monitoring, eruptions at Ruapehu can occur without warning (e.g. 1988 and 2007 eruptions) and generally occur when the vent is inferred to be closed. They result from the sudden release of pressure after it has built up within the hydrothermal system below the lake. These eruptions are likely to be the most hazardous and will not be predictable.

7.2. Recommendations

It is recommended that GNS Science continue the monitoring programme at Ruapehu as the eruptive activity is cyclic, thus the patterns in monitoring data, especially chemical, are also cyclic. With continued monitoring the patterns may occur again and provide successful predictions.

Analysing water samples for polythionic acids should be re-introduced as changes in their concentration appear to parallel eruptive activity, and they may be able to predict future eruptions.

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Appendix A – Ruapehu Eruptive History

Table A.1: Summary of eruptive activity at Ruapehu from 1950 to 2008. The eruption magnitude is a semi-quantitative estimate based on observed effects (Table A.2), (adapted from Houghton *et al.*, 1987; Stevenson, 1992, with additional data from the New Zealand Volcanological Records).

Date	Description of Events	Magnitude	Size of Hazard Zone
26 July 1950	Small phreatic/phreatomagmatic eruption	2	Confined to basin
8 October 1954	Steam columns observed	1	
23 October 1956	Steam columns observed	1	
18 November 1956	Small phreatic/phreatomagmatic eruption	2	Confined to basin
21 May 1959	Small phreatic/phreatomagmatic eruption	2	Confined to basin
1 June – 31 August 1959	Numerous small phreatic/phreatomagmatic eruptions	2	Confined to basin
28 April 1964	Steam column observed	1	
1 – 29 June 1964	Steam columns observed	1	
23 March 1966	Steam column observed	1	
11 August 1966	Small phreatomagmatic eruption	2	Confined to basin
27 September 1966	Small geyser-like events in lake	1	Confined to lake
24 October 1966	Steam columns observed	1	
22 – 30 July 1967	Small geyser-like eruptions	1	
4 October 1967	Hydrothermal eruption	1	
7 April 1968	Geyser-like eruptions in lake	1	Confined to lake outlet

26 April 1968	Moderate phreatomagmatic eruption with lahar down Whangaehu valley	3	10 km radius from vent and Whangaehu valley
23 May – 10 June 1968	Several small phreatomagmatic eruptions	2	Confined to basin
22 June 1969	Major phreatomagmatic eruption. Lahars down Whakapapanui, Whakapapa, Mangaturuturu and Whangaehu valleys	4	Risk to life on summit plateau and in all major valleys; inconvenience due to ash fall up to 25 km from vent
16 September 1970	Small phreatic/phreatomagmatic eruption	2	Confined to basin
3 – 7 April 1971	Small phreatic/phreatomagmatic eruptions	2	Confined to basin
8 May 1971	Moderate phreatomagmatic eruption with lahar down Whangaehu valley	3	Risk to life on summit plateau and Whangaehu valley
15 – 16 May 1971	Numerous moderate eruptions with lahars down Whangaehu valley	3 – 4	Confined to summit plateau and Whangaehu valley
14 July 1971	Small phreatic/phreatomagmatic eruption with lahars down Whangaehu valley	3	Confined to summit plateau and Whangaehu valley
22 October 1972	Three geyser-like eruptions in lake	2	Confined to basin
11 November 1972	Small phreatic eruption	2	Confined to basin
8 January 1973	Small phreatic eruption in lake	1	Confined to lake outlet
October – November 1973	Several very small phreatic eruptions in lake	1	Confined to lake outlet
January – May 1974	Small phreatic eruptions in lake	1	Confined to lake outlet
2 – 5 August 1974	Small phreatic eruptions in lake	1	Confined to lake outlet
September – October 1974	Numerous steam columns	1	

24 April 1975	Major phreatomagmatic eruption. Lahars down Whakapapanui, Whakapapaiti, Mangaturuturu and Whangaehu valleys	5	Risk to life on summit plateau and in all major valleys; ash to a 130 km radius from vent
27 April 1975	Moderate phreatomagmatic eruption	2 – 3	Confined to summit plateau and upper Whangaehu valley
21 October 1975	Small phreatomagmatic eruption	2	Confined to basin
6 April 1976	Small geyser-like eruption	1	Confined to lake
July – August 1977	Several small phreatic eruptions	1	Confined to lake outlet
2 November 1977	Moderate phreatomagmatic eruption with lahar down Whangaehu valley	3	600 m radius from vent and Whangaehu valley
January 1978	Very small phreatic eruptions	1	Confined to lake outlet
7 March 1978	Small phreatic eruption	2	2 km radius from vent
June 1978	Numerous small phreatic eruptions	1	Confined to lake
September 1978	Small phreatomagmatic eruptions	1	Confined to lake
October 1978	Small geyser-like eruptions	1	Confined to lake
January 1979	Numerous small phreatomagmatic eruptions	1	Confined to lake
June – July 1979	Numerous phreatic/phreatomagmatic eruptions	1	Confined to lake
December 1979	Small phreatic/phreatomagmatic eruptions	2	Confined to basin
January 1980	Phreatic/phreatomagmatic eruptions	1	Confined to lake outlet
February – April 1980	Numerous small phreatic/phreatomagmatic eruptions	1 – 2	Confined to basin

18 October 1980	Very small phreatic/phreatomagmatic eruption	2	Confined to basin
October 1981 – April 1982	Several small phreatic/phreatomagmatic eruptions	1 – 2	Confined to basin
2 April 1984	Small phreatic eruption	1	Confined to basin
May – June 1985	Numerous small phreatic eruptions	1	Confined to basin
February 1986	Very small phreatic eruptions	1	Confined to lake outlet
August 1987	Very small phreatic eruptions	1	Confined to lake outlet
March – May 1988	Small phreatic eruptions	1	Confined to basin
8 December 1988	Moderate phreatic eruption with small lahar down Whangaehu valley	3	Summit plateau and Whangaehu valley; ash 1.1 km NE of vent
January – February 1989	Small phreatic eruptions	1	Confined to basin
July 1989	Small phreatic eruptions	1	Confined to basin
January – February 1990	Small phreatic eruptions	1	Confined to basin
February – March 1992	Several minor phreatic eruptions	1	Confined to basin
February – March 1994	Small phreatic eruptions	1	Confined to lake
January – February 1995	Small phreatic eruptions	1	Confined to lake
25 April 1995	Phreatic eruption	1 – 2	Confined to lake
29 June 1995	Phreatic eruption	2	Confined to basin
18 September 1995	Moderate phreatomagmatic eruption with lahar down Whangaehu valley	3	Summit plateau and Whangaehu valley
20 September 1995	Phreatic eruption with small lahar down Whangaehu valley	2	Summit plateau and Whangaehu valley

23 September 1995	Major phreatomagmatic eruption. Lahars down Whakapapanui, Mangaturuturu and Whangaehu valleys	5	Risk to life on summit plateau and in all major valleys; ash 150 km from vent
25 September 1995	Smaller surtseyan type eruptions with large lahar down Whangaehu valley	2 – 3	Summit plateau and Whangaehu valley; ash 10 km E from vent
26 September – 5 October 1995	Smaller phreatomagmatic eruptions	2	Summit plateau
7 October 1995	Large phreatomagmatic eruption with lahar down Whangaehu valley	2 – 3	Summit plateau and Whangaehu valley
11 October 1995	Near-continuous major magmatic eruptions with voluminous ash emissions	5	Risk to life on summit plateau; ash 250 km NE of vent
14 October 1995	Major magmatic eruption with voluminous ash emissions and lahar down Whangaehu valley	5	Risk to life on summit plateau and Whangaehu valley; ash 200 km SE of vent
15 October – November 1995	Degassing-type eruptions and minor ash eruptions	2	Summit plateau
17 June 1996	Major phreatomagmatic eruptions followed by strombolian eruptions with lahar down Whangaehu valley	5	Risk to life on summit plateau and Whangaehu valley; ash to Bay of Plenty coast
18 – 26 June 1996	Variable intensity magmatic eruptions	3	Risk on summit plateau
27 June 1996	Large magmatic eruptions followed by ash eruptions	4	Risk to life on summit plateau
28 June – 3 July 1996	Intermittent minor ash eruptions	3	Summit plateau and area surrounding

			mountain
4 July 1996	Large ash eruption	4	Summit plateau; ash 40 km downwind from vent
8 July 1996	Large near-continuous strombolian eruptions	5	Risk to life on summit plateau
9 – 14 July 1996	Intermediate strombolian and vulcanian eruptions	3	Risk to life on summit plateau
15 July 1996	Ash eruptions	2 – 3	Summit plateau and area surrounding mountain
16 July 1996	Several large magmatic eruptions with large ash plumes	4	Risk to life on summit plateau
17 – 19 July 1996	Minor ash eruptions	2	Summit plateau and area surrounding mountain
20 July 1996	Large magmatic eruptions with large ash plumes and fire fountaining	5	Risk to life on summit plateau; ash east of the vent
21 July – 31 August 1996	Minor ash eruptions	2	Summit plateau and area surrounding mountain
1 – 9 September 1996	Minor eruptions with local ash falls	3	Summit plateau and area surrounding mountain
12 October 1997	Minor phreatic eruptions	2	Confined to basin
1 November 1997	Minor phreatic eruptions	2	Confined to basin
8 November 1998	Small phreatic eruptions	1	Confined to basin
4 October 2006	Minor hydrothermal eruption	2	Confined to basin

25 September 2007	Moderate hydrothermal eruptions with lahars down Whangaehu valley and Whakapapa ski field	3	Confined to summit plateau and Whangaehu valley and Whakapapa ski field

Table A.2: Semi-quantitative estimate of the magnitude of Ruapehu eruptions based on observed effects (from Sherburn *et al.*, 1999).

Magnitude	**Observed Effects**
1	Small phreatic eruptions confined to Crater Lake
2	Phreatic eruption accompanied by surges; material deposited outside Crater Lake, but still confined to the crater basin
3	Deposition of material out side the crater basin; possible lahars in Whangaehu valley
4	Larger lahars; more material deposited outside the crater basin
5	Lahars in valleys other than the Whangaehu; material deposited more than a few kilometres from the vent

Appendix B – Ruapehu Monitoring Data

Table B.1: Monitoring data from Ruapehu from 1960 to 2008 (sourced from GNS Science).

Date	Lake Temperature (°C)	Mg^{2+} (ppm)	Cl^- (ppm)	Mg/Cl Ratio	Crater Diameter (m)	SO_2 Emission (t/d)	CO_2 Emission (t/d)	$H_2S_xO_6$/Cl Ratio
21/01/1960	27.0		3980					
20/01/1961	27.0							
20/02/1962	26.0							
20/03/1964	22.0							
09/05/1964		780	8500	0.134				
26/05/1964	41.5							
15/05/1965	16.0							
18/06/1965	16.6							
07/09/1965	23.5							
05/12/1965	29.5							
15/12/1965	30.0							
24/12/1965	32.0							
10/01/1966	33.0	550	7600	0.072				
28/01/1966	40.0							
10/02/1966	40.0							
15/02/1966	49.5	625	7890	0.079				
09/03/1966	46.6	600	7965	0.075				
25/03/1966	47.0	600	8060	0.074				
02/04/1966	42.0	640	8050	0.080				
14/04/1966	36.5	675	8240	0.082				
05/05/1966	33.0	670	8092	0.083				
20/05/1966	33.5							
18/06/1966	31.0							
20/06/1966	31.0	600	8310	0.072				
25/07/1966	53.0	665	8485	0.078				
28/07/1966	54.0							
30/07/1966	53.8							
03/08/1966	53.0	810	8850	0.092				
11/08/1966	48.8	665	9070	0.083				
19/08/1966	50.5	915	9240	0.099				
21/08/1966	50.5							
01/09/1966	49.5	975	9488	0.103				
13/09/1966	44.0	1000	9710	0.103				
27/09/1966	41.0	970	9854	0.098				
18/10/1966	50.0	1020	10190	0.100				
11/11/1966	44.3	1050	10485	0.100				
15/12/1966	31.7	1154	10590	0.109				
11/01/1967	39.0							
24/01/1967	39.5	1050	10710	0.098				
14/02/1967	39.0	939	10548	0.089				
16/02/1967	39.0							
24/02/1967	39.0		10548					
15/03/1967	39.5		10280					

14/04/1967	37.5	885	10406	0.085				
17/04/1967	37.5							
13/06/1967	33.0	925	10886	0.085				
09/08/1967	41.5	961	11176	0.086				
12/12/1967	26.5	959	11151	0.086				
22/01/1968	36.0							
01/03/1968	38.0		11064					
07/04/1968	53.5	1010	11347	0.095				
29/04/1968	60.0		11915					
07/05/1968	51.0		12100					
23/05/1968	43.0	1269	12560	0.101				
06/06/1968	55.0		13295					0.0000
11/06/1968	47.5	1461	13405	0.109				
21/06/1968	51.5	1610	13420	0.120				
05/07/1968	34.0		13225					0.0000
08/08/1968	29.5	1547	13113	0.118				0.0000
21/08/1968	33.5		13110					
13/09/1968	20.6	1442	13110	0.110				
01/11/1968	25.5							0.0013
11/12/1968	29.0	1211	12613	0.096				0.0037
19/01/1969	33.0							
20/01/1969	33.0							
22/01/1969	33.0							
08/02/1969	33.0		12315					0.0506
20/03/1969	29.8	1177	12010	0.098				
06/04/1969	24.0							
05/05/1969	23.0							
26/06/1969	43.0	1430	11496	0.124				0.0053
04/07/1969	35.4							
12/07/1969	38.0	1408	11446	0.123				
14/08/1969	33.0	1488	11446	0.130				
25/08/1969	36.0							
06/09/1969	42.0	1578	11600	0.136				
23/09/1969	36.0							
04/10/1969	38.0	1580	11640	0.136				0.0000
06/11/1969	36.5	1560	11900	0.131				0.0000
06/12/1969	40.0							0.0011
23/12/1969	39.0	1400	11300	0.124				
05/01/1970	40.5							0.0009
12/01/1970								0.0000
18/01/1970	37.0	1430	11300	0.127				0.0011
25/01/1970	38.0							
26/01/1970	38.0							0.0007
12/04/1970	35.0	1180	11400	0.104				
12/05/1970	35.0							
25/06/1970	33.6	1220	11400	0.107				
11/08/1970	28.5	1200	11700	0.103				0.0942
22/09/1970	34.0							
08/11/1970	26.0	1200	10800	0.111				0.0000
09/12/1970	25.0	1080	10000	0.108				
24/03/1971	27.5							
31/03/1971	34.5	1020	9400	0.109				

02/04/1971	36.0							
07/04/1971	38.0	1050	9600	0.109				
12/04/1971	41.5	1100	9800	0.112				
22/04/1971	38.0	1120	9800	0.114				
29/04/1971	55.0	1130	9850	0.115				
08/05/1971	46.5	1270	10000	0.127				0.0000
15/05/1971	47.0	1330	10200	0.130				
17/05/1971	60.0	1430	10400	0.130				
18/06/1971	48.0							
21/06/1971	45.0							
14/07/1971	53.0							
15/07/1971	53.0	2380	12100	0.197				
20/07/1971	52.0							
20/08/1971	53.0	2300	12350	0.186				
23/08/1971	55.0							
16/09/1971	47.5							
15/10/1971	37.5	2420	13460	0.180				
01/11/1971	36.0	2380	13570	0.175				
22/12/1971	41.0	2320	13710	0.169				
23/12/1971	40.0							
27/01/1972	40.5	2000	12600	0.159				
15/03/1972	35.0	1930	12420	0.155				
16/03/1972	35.0							
02/04/1972	32.0	1970	12890	0.153				
21/04/1972	31.5	2000	13130	0.152				
08/05/1972	28.0	2030	13150	0.154				
28/06/1972	30.5	1950	13260	0.147				
29/06/1972	30.0							
26/07/1972	23.0	1890	13200	0.143				
05/09/1972	18.8	1845	13120	0.141				
07/09/1972	18.8							
02/10/1972	22.2	1810	12950	0.139				
22/10/1972	38.0	1800	13200	0.136				
11/11/1972	38.0	1750	13240	0.132				
10/01/1973	41.0	1660	12990	0.128				
11/01/1973	41.0							
06/02/1973	40.0	1590	12650	0.126				
26/02/1973	41.0	1580	12240	0.124				0.0000
29/03/1973	35.0	1518	12370	0.114				0.0210
23/05/1973	34.1	1446	12350	0.110				0.0000
18/06/1973	30.0	1412	12440	0.110				0.0074
4/07/1973								0.0356
05/07/1973	32.0	1409	12400	0.111				0.0288
25/08/1973	28.0	1380	12650	0.108				0.0408
31/10/1973	37.0	1305	12680	0.103				0.0039
11/11/1973	44.0	1275	12480	0.102				0.0068
23/11/1973	35.0	1255	12375	0.103				0.0155
15/01/1974	32.0	1120	11790	0.095				0.0370
26/01/1974	36.0	1175	12100	0.097				0.0259
09/03/1974	38.0	1145	11945	0.096				0.0148
12/03/1974	41.0	1165	12200	0.095				0.0155
22/03/1974	36.5	1160	12300	0.094				

29/03/1974	38.0	1160	12190	0.095				0.0084
12/04/1974	38.0							
13/04/1974	38.0							
12/05/1974	33.5	1185	12424	0.095				0.0023
01/07/1974	26.8	1192	12452	0.096				0.0000
08/08/1974	27.0							
09/08/1974	29.5	1192	12459	0.096				0.0351
13/09/1974	32.0	1270	12500	0.098				0.0411
25/10/1974	28.5	1290	12370	0.104				0.0281
29/10/1974	28.5							
12/12/1974	30.5	1240	12500	0.099				0.0485
26/12/1974	38.0	1175	12100	0.097				
22/01/1975	25.5	1090	11290	0.097				
22/02/1975								0.0811
19/03/1975	28.8	1080	11100	0.098				0.0842
08/04/1975	24.8	1040	10680	0.097				0.0757
29/04/1975	46.0	1430	11150	0.128				0.0030
08/05/1975	43.0	1540	11280	0.137				0.0000
18/06/1975	34.0	1550	10370	0.149				0.0000
30/06/1975	34.0							
25/07/1975	28.3	1560	10810	0.144				0.0000
10/09/1975	24.0	1292	9210	0.140				0.0000
21/10/1975	29.0	1440	10180	0.141				0.0000
22/10/1975	29.0							
11/11/1975	29.0	1450	10140	0.143				0.0000
23/12/1975	26.0	1460	9680	0.151				0.0000
04/01/1976	27.2	1480	9640	0.153				
19/01/1976	24.5	1330	8860	0.150				0.0000
21/01/1976	23.0	1330	8900	0.149				
04/02/1976	22.5	1290	8540	0.151				0.0000
05/02/1976	22.5							
24/02/1976	23.0	1190	7730	0.154				0.0000
25/02/1976	22.0							
02/03/1976	25.3	1260	8330	0.151				0.0000
09/03/1976	22.0	1040	6740	0.154	600.013			0.0000
06/04/1976	30.5	1230	8140	0.151				0.0000
05/05/1976	27.5	1210	7850	0.154				
07/06/1976	21.2	1230	7780	0.158	600.013			0.0000
05/07/1976	21.0							0.0000
06/07/1976	21.0	1210	7670	0.158				
19/08/1976	21.0	1260	7730	0.163				0.0000
21/09/1976	28.2	1270	7620	0.167				0.0000
17/11/1976	22.0	1250	7490	0.167				
18/11/1976	22.0							
23/11/1976	24.5	1290	7660	0.168				
16/01/1977	18.8	1180	7320	0.161				
09/02/1977	22.0	970	6226	0.156				0.0000
17/02/1977	23.5	1020	6651	0.153	600.026			
15/03/1977	25.5	1090	7161	0.152				
10/05/1977	23.5	1010	7242	0.139				0.0000
20/06/1977	21.5	920	7170	0.128				
05/07/1977	18.0	930	7110	0.131	600.033			

12/08/1977	31.0	1115	7440	0.150				
23/09/1977	30.5	1150	7520	0.153				
27/10/1977	31.0	1195	7495	0.159				
09/11/1977	32.5	1320	7890	0.167				0.0000
07/12/1977	30.0	1100	6520	0.169				
15/01/1978	26.0	1220	7560	0.161	600.024			
17/01/1978	27.0							
10/02/1978	38.0	1240	7870	0.158				
21/02/1978	32.5	1215	7615	0.160				
08/03/1978	31.5	1190	7430	0.160				
14/03/1978	36.0	1235	7760	0.161	600.031			0.0000
13/04/1978	35.0	1230	7790	0.158				
30/05/1978	43.0	1169	8390	0.139				0.0072
13/06/1978	43.0	1185	8710	0.136				0.0000
15/06/1978	48.3				600.030			0.0000
16/06/1978	48.3							
18/07/1978	30.0	1205	8920	0.135				
19/07/1978	30.0							
31/08/1978	24.5	1180	8930	0.132				
08/09/1978	31.0	1175	8890	0.132				0.0000
09/10/1978	27.5	1180	8990	0.131				
29/11/1978	32.0	1150	9020	0.127				
11/01/1979	27.0	1120	8590	0.130	600.028			
02/02/1979	32.0	1180	8700	0.136				
05/02/1979	32.0							
26/03/1979	33.5	1050	7600	0.139				
02/04/1979	31.5	1130	7920	0.143	600.021			
02/05/1979	31.5							
06/06/1979	18.5	1095	7565	0.145				0.0065
20/07/1979	26.5	1070	8050	0.133	600.024			
17/08/1979	24.0	1055	8035	0.131				
28/09/1979	21.7	1040	8320	0.125				
26/10/1979	21.5	1010	8230	0.123				
06/12/1979	18.0	920	7700	0.120				
15/01/1980	22.0	855	7180	0.119	600.019			
12/02/1980	34.0	855	7370	0.166				
20/02/1980	43.0	855	7185	0.119				
29/02/1980	41.0	875	7470	0.117				
14/03/1980	37.5	885	7380	0.120				
27/03/1980	40.0	885	7430	0.119				
12/04/1980	37.0	890	7545	0.118	600.025			
07/05/1980	39.0	900	7625	0.118				
30/05/1980	31.0	895	7730	0.116				
03/06/1980	31.5							
20/06/1980	30.0	880	7595	0.116				
27/06/1980	30.0	885	7740	0.116				
29/07/1980	26.8	860	7400	0.116	600.045			
10/08/1980	23.0	840	7450	0.113	600.015			
11/08/1980	23.0							
02/09/1980	18.5	820	7450	0.110	600.022			
24/09/1980	16.5	800	7300	0.110				
07/10/1980	25.0	780	7150	0.109				

22/10/1980	31.0							
30/10/1980	31.0	740	6850	0.108				
19/11/1980	35.0	770	7300	0.105				
02/01/1981	33.0	745	7320	0.106				
05/01/1981	33.0							
29/01/1981	38.0							
19/02/1981	33.6	715	7080	0.102	600.020			
20/03/1981	33.5	700	7100	0.099				
23/04/1981	32.5	610	6100	0.100				
11/06/1981	24.0	710	6970	0.102				
12/06/1981	24.0							
06/08/1981	14.2	680	6820	0.100				
12/08/1981	13.0							
17/08/1981	15.0							
28/08/1981	13.4	655	6735	0.097	600.036			
08/10/1981	10.5	620	6750	0.092				
13/10/1981	11.8	630	6750	0.093	600.008			
04/11/1981	24.0	615	6770	0.091				
21/11/1981	36.5							
24/11/1981	42.0	625	6903	0.091				0.0000
28/12/1981	46.8	663	6930	0.096				
12/01/1982	57.2	765	7400	0.103	600.037			0.0000
21/01/1982	57.0	853	7730	0.110	600.024			0.0000
05/02/1982	49.0	1025	7884	0.130				0.0000
11/02/1982	50.5	990	7875	0.126	600.030			0.0000
05/03/1982	41.0	953	7939	0.120				
23/03/1982	23.0	977	7875	0.124	600.029			0.0000
15/04/1982	39.0	1023	8168	0.125	600.039			0.0000
21/04/1982	42.0	998	8206	0.122	600.032			0.0000
29/05/1982	27.0	1018	8344	0.122	600.043			0.0009
02/07/1982	33.0	1025	8594	0.119	600.036			0.0013
05/07/1982	33.0							
23/07/1982	24.5	997	8690	0.115	600.032			0.0076
20/08/1982	23.0							
24/08/1982	24.0	1005	8740	0.115	600.034			0.0076
17/09/1982	29.0	1010	8950	0.113	600.034			0.0063
21/10/1982	25.0	1022	8850	0.115	600.033			0.0172
09/11/1982	21.0	988	8725	0.113	600.041			0.0193
15/12/1982	13.0	900	8240	0.109	600.065			0.0237
03/01/1983	22.0	870	8390	0.104	600.015			
24/01/1983	20.5	850	7930	0.107	600.024			
29/01/1983	28.5	654	7290	0.090	600.041			
02/02/1983	23.5	784	7315	0.107	600.031			
10/02/1983	19.0							0.0534
11/02/1983	19.0	875	8165	0.107	600.036			
22/02/1983	23.5	784	7315	0.107	600.031			0.0349
24/02/1983	23.5							
28/02/1983	27.0	844	8015	0.105	600.022			0.0535
17/03/1983	23.0	820	7880	0.104	600.014			0.0533
21/03/1983	23.0							
18/04/1983	20.0	565	6210	0.091	600.013			0.0080
24/04/1983	20.0							

15/05/1983	16.5	754	7465	0.101	600.030			0.0675
18/05/1983	16.5							
15/06/1983	16.5							0.0789
22/06/1983	16.5	751	7455	0.101	600.009			
18/07/1983	18.7	778	7310	0.106	600.021			
16/08/1983	18.3	744	7470	0.100	600.027			0.0986
23/09/1983	18.0							
29/09/1983	18.0	690	7320	0.094	600.028			
09/11/1983	21.0	447	4875	0.092	600.012			
29/11/1983	28.5	654	7290	0.090	600.041			
06/12/1983	28.5							
02/01/1984	29.5	652	7410	0.088	600.036			
08/02/1984	31.0	648	7430	0.087				0.0936
09/02/1984	31.0							
21/02/1984					600.051			
20/03/1984	25.0	604	7135	0.085	600.005			0.0662
04/05/1984	18.3	597	7045	0.085	600.021			0.1021
09/05/1984	18.3							
04/06/1984	13.4	574	7160	0.080	600.021			
4/07/1984								0.1093
18/07/1984	11.6	552	6980	0.079	600.016			0.0607
04/08/1984	13.4							
18/08/1984	11.6							
17/09/1984	16.5	537	6830	0.076	600.000			0.0858
25/10/1984	21.0	538	7070	0.076	600.022			0.0694
29/10/1984	21.0							
19/12/1984	16.0	407	5340	0.076	600.025			0.0618
31/01/1985	23.0	455	5775	0.079	600.027			0.1312
26/02/1985	23.0	426	6040	0.071	600.021			0.0983
05/03/1985	23.0							
19/03/1985	21.5	400	5740	0.070	600.032			0.1163
21/03/1985	21.5							
28/03/1985					600.020			
11/04/1985								0.0000
26/04/1985					600.023			
28/05/1985	45.0	439	6410	0.068				0.0715
03/06/1985	45.0	454	6425	0.071				0.0000
04/06/1985	44.0	461	6255	0.074	600.020			0.0485
26/06/1985	36.5	485	6565	0.074	600.019			
27/06/1985	38.0							
11/07/1985	31.5	496	6820	0.073				
05/08/1985	32.0	493	6835	0.072	600.020			0.0000
06/08/1985	32.0							
14/09/1985	21.0	494	7025	0.070				0.0105
20/09/1985	21.7				600.022			0.1771
17/10/1985	20.0	501	7050	0.072	600.030			0.0105
18/10/1985	20.0							
31/10/1985	26.5	508	7270	0.070				0.0000
15/11/1985	36.0	507	7360	0.069	600.019			0.0000
05/12/1985	36.0	498	7720	0.065	600.041			0.0000
13/12/1985	35.0	499	7690	0.065	600.027			0.0000
14/01/1986	29.0	435	7200	0.060	600.034			0.0000

11/02/1986	46.0	480	8020	0.060	600.027			0.0000
14/02/1986	45.5	476	7980	0.060	600.031			0.0000
26/02/1986	34.0	467	7630	0.061				0.0000
07/03/1986	35.0							
19/03/1986	32.0	473	7380	0.064				0.0088
21/03/1986					600.036			
08/05/1986	22.0	476	7825	0.061	600.031			0.0140
19/07/1986	13.5	455	7550	0.060				0.0106
31/07/1986	10.8	499	7810	0.064	600.023			0.0071
26/08/1986	14.5	475	7580	0.063	600.024			0.0000
02/09/1986	17.0							
14/09/1986	18.0	464	7395	0.063				0.0000
09/10/1986	21.0	457	8165	0.056				0.0000
15/10/1986	23.0	471	8385	0.056	600.027			0.0000
02/11/1986	31.5	468	8080	0.058				0.0000
20/11/1986	34.0	477	8025	0.059	600.035			0.0237
17/12/1986	20.0	429	7170	0.060	600.043			0.0000
13/01/1987	21.0	418	6790	0.062	600.036			0.0000
15/01/1987	21.0							
25/02/1987	21.5	453	7220	0.063	600.036			0.0232
15/04/1987	19.0	410	6720	0.061	600.036			
04/05/1987	12.0	430	6720	0.064				
26/05/1987	14.2	420	6720	0.063	600.037			
03/07/1987	11.5	430	6520	0.066	600.034			
13/08/1987	24.5	420	6590	0.064	600.042			0.0000
30/08/1987	40.0	430	6880	0.063				0.0000
10/09/1987	38.0	440	6880	0.064	600.041			0.0000
28/09/1987	30.5	440	7130	0.062				0.0000
16/10/1987	28.5	440	6880	0.064	600.055			0.0000
12/11/1987	27.0	420	6970	0.060	600.047			0.0000
19/12/1987	17.0	360	6060	0.059	600.043			0.0000
21/12/1987	17.0							
13/01/1988	20.0	410	6610	0.062	600.046			0.0000
17/01/1988	23.5	400	6940	0.058				0.0000
25/01/1988	20.0	310	5350	0.058				0.0373
02/02/1988	23.5	360	6060	0.059				0.0261
15/02/1988	16.5	310	5330	0.058				0.0466
01/03/1988	18.5	310	5330	0.058	600.049			0.0344
22/03/1988	31.8	400	6610	0.061	600.047			0.0494
12/04/1988	38.8	420	6790	0.063				0.0289
03/05/1988	36.5	460	7160	0.064	600.049			0.0335
01/06/1988	25.5	450	6888	0.066	600.046			0.0236
02/06/1988	25.5							
21/06/1988	22.5	440	6714	0.065	600.044			0.0456
04/08/1988	14.0	430	6737	0.064	600.042			0.0477
14/08/1988								0.0539
15/09/1988	10.0	400	6440	0.062	600.043			0.0674
17/10/1988	10.5	390	6270	0.062	600.039			0.0827
18/10/1988	10.5							
14/11/1988	9.0	340	5466	0.062	600.041			
09/12/1988	13.7	340	5531	0.061	600.034			0.0905
16/12/1988	14.0	350	5478	0.064				0.0214

11/01/1989	27.0	280	3983	0.071	600.040			0.0000
24/01/1989	32.2	380	5727	0.067				0.0960
10/02/1989	39.0	410	5804	0.071				0.0265
26/02/1989	42.5	410	5812	0.071	600.040			
21/03/1989	32.0	430	6126	0.070	600.055			0.0000
22/03/1989	32.0							
05/04/1989	31.3	430	6164	0.070	600.047			0.0411
11/05/1989	25.0	430	6168	0.070	600.046			0.0558
18/05/1989	25.0							
14/06/1989	13.8	420	5670	0.074	600.042			0.0654
19/07/1989								0.0592
24/07/1989	33.7	426	6364	0.067	600.043			
09/08/1989	32.8	430	6465	0.067				0.0000
05/09/1989	34.6	438	6731	0.065	600.051			0.0670
19/10/1989	26.0	450	6960	0.065	600.060			0.0415
17/11/1989	23.0	440	6738	0.065	600.051			0.0531
11/12/1989	22.0	430	6641	0.062	600.045			0.0605
11/01/1990	25.3	380	6158	0.062	600.050			0.0348
26/01/1990	42.1	400	6551	0.061				0.0396
01/02/1990	46.7	390	6577	0.059	600.051			
08/02/1990	46.7							
16/02/1990	46.5	400	6630	0.060				
19/03/1990	34.1	400	6328	0.063	600.046			0.0000
22/03/1990	30.0							
24/03/1990	36.0							
28/03/1990	30.0							
29/03/1990	22.9							
30/03/1990	28.0							
05/04/1990	30.5							
06/04/1990	30.0							
11/04/1990	32.0							
12/04/1990	29.5	356	6144	0.058	600.043			0.0236
10/05/1990	25.8	361	6526	0.055	600.049			
21/05/1990	25.8							
17/06/1990	23.5	355	6650	0.053	600.056			
20/07/1990	20.0	362	6717	0.054	600.053			
22/08/1990	25.0	336	6624	0.051	600.071			
29/08/1990					600.072			
11/09/1990	30.0	361	6891	0.052	600.066			
26/09/1990					600.062			
09/10/1990	31.0	368	6933	0.053	600.066			
27/12/1990	24.0	322	6989	0.046	600.057			0.0616
13/01/1991	29.0	355	6933	0.051				
18/01/1991	27.0	335	6859	0.049				
20/01/1991	17.5	288	6730	0.043				
03/02/1991	23.0							
08/02/1991	21.0							
09/02/1991	21.0	312	6564	0.048	600.060			0.0668
21/03/1991	26.7	321	6711	0.048	600.051			
03/05/1991	18.0	312	6526	0.048	600.058			
14/06/1991	16.0	326	6730	0.048	600.045			
29/08/1991	12.0	300	6539	0.047	600.058			

17/10/1991	13.8	296	6401	0.046	600.050			
20/11/1991	17.8	288	6284	0.046				
03/01/1992	22.1	295	6238	0.047	600.038			
11/02/1992	39.0	295	6245	0.047	600.046			
24/03/1992	31.5	310	6668	0.046	600.060			
06/05/1992	34.5	313	7060	0.044	600.062			
17/07/1992	17.2	308	7200	0.043	600.042			
13/09/1992	10.2	286	6778	0.042				
28/10/1992	11.8							
29/10/1992	11.8							
21/12/1992	28.2	292	6695	0.044				
12/01/1993	21.0	273	5974	0.046				
18/01/1993	21.0							
17/02/1993	24.0	299	6674	0.045	600.048			
28/02/1993	28.5	287	6519	0.044				
01/03/1993	28.0	287	6519	0.044				
02/03/1993	29.0							
23/03/1993	23.0	284	6477	0.044				
20/04/1993	21.0	278	6354	0.044	600.054			
03/06/1993	14.0	282	6403	0.044	600.050			
18/06/1993	10.9	273	6194	0.044				
03/07/1993	11.2	277	6267	0.044				
06/08/1993	19.6	277	6404	0.043				
21/09/1993	35.5	283	6753	0.042				
29/09/1993	38.2	282	6883	0.041				
09/10/1993	35.5	294	7016	0.042				
04/11/1993	37.2	296	7233	0.041	600.048			
10/12/1993	26.0	293	7175	0.041				
18/01/1994	25.2	255	6642	0.038				
28/01/1994	32.7	278	7174	0.039	600.057			
10/02/1994	36.0	253	6646	0.038				
18/02/1994	39.0	271	7118	0.038				
26/02/1994	38.5							
06/03/1994	32.0							
28/03/1994	25.0	277	7195	0.038				
18/04/1994	23.0	272	7150	0.038				
06/05/1994	19.0	270	7128	0.038	600.060			
08/06/1994	21.0							
04/07/1994	22.0	262	7029	0.037				
12/08/1994	16.0	255	6875	0.037				
27/08/1994	17.0	254	6844	0.037				
27/10/1994	17.0	238	6404	0.037				
07/12/1994	22.0	239	6451	0.037				
13/01/1995	41.5	241	6652	0.036				
18/01/1995	46.5	237	6662	0.036				
29/01/1995	51.4	235	6719	0.035				
02/03/1995	45.5	243	7018	0.035	600.042			
19/04/1995	31.0	226	6989	0.032	600.041			
04/05/1995	46.0	278	7235	0.038				
25/05/1995	45.9	385	7603	0.051				
16/06/1995	38.0	427	7797	0.055				
04/07/1995	33.0	514	7976	0.064	600.046			

18/07/1995	31.0	551	8014	0.069				
15/08/1995	29.0	584	8154	0.072	600.040			
20/09/1995	48.0	713	8619	0.083	600.062			
25/09/1995						2600.0		
28/09/1995						1500.0		
01/10/1995						300.0		
03/10/1995						300.0		
04/10/1995						470.0		
13/10/1995						15800.0		
17/10/1995						14000.0		
20/10/1995						1900.0		
29/10/1995						2000.0		
03/11/1995		310	1732	0.179		6300.0		
07/11/1995						2150.0		
22/11/1995						960.0		
28/11/1995						1350.0		
06/12/1995	57.7	903	12536	0.072				
20/12/1995	60.0	612	8127	0.075				
31/12/1995						1300.0		
18/01/1996	49.6	367	5664	0.065				
25/02/1996	55.0	183	2684	0.068				
28/02/1996						500.0		
27/03/1996	49.6	378	4343	0.087				
11/05/1996	65.6	705	8103	0.087				
19/06/1996						4100.0		
28/06/1996						5100.0		
15/07/1996						6000.0		
24/07/1996						9000.0		
08/08/1996						5500.0		
03/10/1996						1700.0		
28/02/1997	60.5	1730	10168	0.170				
30/07/1997	62.0	2800	23684	0.118				
24/09/1997	63.0	2780	26840	0.104				
01/02/1998	61.0	3490	24280	0.144				
17/03/1998	53.0	3050	21531	0.142				
27/03/1998	60.0	2960	20870	0.142				
04/08/1998	55.8	2040	15427	0.132				
08/11/1998	69.0	1620	13363	0.121				
27/11/1998	57.9	1740	14262	0.122				
10/01/1999	52.5	1529	13487	0.113				
22/03/1999	56.5	1276	12795	0.100				
13/04/1999	60.8	1434	12497	0.115				
10/07/1999		1360	13437	0.101				
10/08/1999	58.0	1474	14625	0.101				
19/08/1999	51.0	1507	14758	0.102				
27/08/1999	56.1	1460	14198	0.103				
17/09/1999	58.0	1442	14455	0.100				
01/10/1999	55.0	1499	14513	0.103				
28/03/2000	39.4	1271	9507	0.134				
20/06/2000	41.0	1410	9316	0.151				
04/09/2000	38.8	1547	9253	0.167				
06/12/2000	33.8	1329	8680	0.153				

04/02/2001	33.7	1292	7620	0.170				
19/02/2001	38.0	1249	7655	0.163				
22/03/2001	37.5	1241	6163	0.201				
24/04/2001	32.5	1270	7620	0.167				
21/06/2001	23.8	1076	7398	0.145				
13/08/2001	21.7	1076	7253	0.148				
27/08/2001	20.5	1018	7389	0.138				
11/09/2001	21.1	1028	7313	0.141				
25/11/2001	22.2	1034	7088	0.146				
08/01/2002	36.3	992	6995	0.142				
21/01/2002	37.5	959	7136	0.134				
02/02/2002	36.4	1006	6942	0.145				
18/02/2002	35.6	964	6903	0.140				
19/02/2002	37.7	983	6919	0.142				
05/04/2002	29.7	994	6895	0.144				
17/04/2002	28.4	957	6734	0.142				
02/08/2002	20.0	806	6418	0.126				
23/08/2002	19.7	950	6570	0.145				
30/08/2002	19.4	870	6564	0.133				
17/09/2002	19.3	869	6600	0.132				
02/10/2002	18.9	907	6493	0.140				
23/10/2002	19.3	902	6849	0.132				
26/11/2002	24.7	1081	7326	0.148				
05/12/2002	34.9	877	6722	0.130				
16/12/2002	34.8	886	6793	0.130				
30/12/2002	38.6	898	6134	0.146				
06/01/2003	42.6							
16/01/2003	40.0	896	6812	0.132				
21/01/2003	38.3	908	6576	0.138				
31/01/2003	31.8	772	6271	0.123				
05/03/2003	30.0	937	6872	0.136				
15/03/2003	35.0	879	6673	0.132				
03/04/2003	37.9	875	7073	0.124				
29/04/2003	39.5	964	7110	0.136				
14/05/2003	41.6	943	7140	0.132				
27/05/2003						0.0	417.0	
29/05/2003	36.0	921	7174	0.128				
01/06/2003	33.0	875	6925	0.126				
27/06/2003	24.4	979	7368	0.133				
13/07/2003	23.4	968	6912	0.140				
23/07/2003	24.8	1034	7306	0.142				
05/08/2003	24.2	888	7305	0.122				
25/08/2003	23.2	948	7398	0.128				
12/09/2003	20.1	1010	7254	0.139				
06/10/2003	18.2	884	7029	0.126				
05/11/2003	17.3	908	7240	0.125				
18/12/2003	19.4	881	6894	0.128				
31/12/2003	20.0							
11/01/2004	24.0							
17/01/2004	23.0							
23/01/2004	23.0	833	6517	0.128				
27/01/2004	23.0	949	6708	0.141				

23/02/2004	15.5	652	4964	0.131				
27/02/2004	20.8	801	6366	0.126				
06/03/2004	25.0							
10/03/2004	28.6	790	6614	0.119				
15/03/2004	35.0							
25/03/2004	32.0					10.6	186.0	
10/04/2004	28.6							
14/04/2004	26.0	789	6404	0.123				
21/04/2004						25.7	538.0	
17/05/2004	24.2	819	6332	0.129				
21/05/2004						21.0	406.0	
10/06/2004	21.0	813	6644	0.122				
08/07/2004						0.0	137.0	
09/07/2004	19.8	856	6483	0.132				
25/07/2004		770	6322	0.122				
03/08/2004	19.5	793	6270	0.126				
20/08/2004	16.6	832	6158	0.135				
21/09/2004	14.3	759	6408	0.118				
21/10/2004	15.8	758	6465	0.117				
13/11/2004	18.9	681	5975	0.114				
19/11/2004	19.3	795	6277	0.127				
07/12/2004	19.1	741	6207	0.119				
15/12/2004	21.0	758	6113	0.124				
26/12/2004	27.0							
12/01/2005	28.3	793	6925	0.115		12.5	757.0	
16/01/2005	32.1							
20/01/2005	30.2	778	6124	0.127				
06/02/2005	39.0							
09/02/2005	39.0	789	6341	0.124				
23/02/2005	36.7	789	6241	0.126				
02/03/2005	34.5	778	6255	0.124				
12/03/2005	33.2	737	6310	0.117				
20/03/2005						8.4	396.0	
06/04/2005	28.5	736	6032	0.122				
15/04/2005						11.5	407.0	
06/05/2005	25.2	654	6255	0.105				
09/06/2005	19.0	727	6258	0.116		14.6	340.0	
13/06/2005	19.0							
27/06/2005	18.0							
30/07/2005	21.0							
04/08/2005	23.3	787	6391	0.123		7.4	861.0	
19/08/2005						18.3		
21/08/2005	32.2	676	6160	0.110				
31/08/2005	37.8	692	6561	0.105				
03/09/2005	38.0							
24/09/2005	34.3	744	6652	0.112				
12/10/2005	31.2	739	6845	0.108				
18/10/2005						22.6	708.0	
24/10/2005	35.6							
27/10/2005	36.5	764	6945	0.110				
11/11/2005						25.6	710.0	
14/11/2005	39.0							

16/11/2005	38.8	783	6994	0.112				
28/12/2005	28.3	864	7118	0.121				
11/01/2006						4.6	137.0	
15/01/2006	24.3							
27/01/2006	24.5							
16/02/2006	30.8	703	6441	0.109				
26/02/2006	29.9							
01/03/2006	28.3	729	6947	0.105				
18/03/2006	27.3	645	6347	0.102				
20/04/2006	25.1	769	6884	0.112		0.0	496.0	
20/05/2006	29.1	727	6845	0.106				
01/06/2006						9.3	375.0	
02/06/2006	32.0	685	6840	0.100				
27/06/2006	24.3					0.0	191.0	
09/07/2006	20.8	770	7288	0.106				
17/07/2006	19.3							
25/07/2006	19.3	802	6777	0.118				
28/07/2006						0.0	1787.0	
24/08/2006	16.6	759	6635	0.114				
28/08/2006						0.0	90.0	
12/09/2006	15.5	739	6728	0.110				
24/09/2006	14.9							
07/10/2006	22.2	763	6773	0.113				
26/10/2006	25.6	752	6662	0.113		1.8	71.0	
01/11/2006	27.2	739	6688	0.110				
13/11/2006	24.6							
29/11/2006	21.8							
24/12/2006	23.5							
29/12/2006	21.8							
04/01/2007	26.2	791	6522	0.121				
05/01/2007	26.2					18.9	283.0	
07/01/2007	26.5							
15/01/2007	25.5							
17/01/2007	26.5	776	6483	0.120				
27/01/2007	27.4							
02/02/2007	27.6							
14/02/2007	28.3	736	6111	0.120				
19/02/2007	28.2	729	6475	0.113				
09/03/2007						55.1	597.0	
23/03/2007	24.2	730	6304	0.116				
20/04/2007	22.5					33.6	115.0	
30/05/2007	19.4	747	6353	0.118				
18/06/2007						48.3	412.0	
14/08/2007	13.5							
15/08/2007	13.5	692	6304	0.110				
23/08/2007						13.0	178.0	
08/09/2007	14.0	792	6248	0.127				
28/09/2007	19.0	848	6345	0.134		13.6		
09/10/2007						40.7	592.0	
20/10/2007	28.2	1046	6866	0.152				
29/10/2007						445.9	895.0	
30/10/2007	32.0	1057	6869	0.154				

09/11/2007						271.0		
20/11/2007	34.0	958	6534	0.147				
21/11/2007						86.4	224.0	
21/12/2007	37.6	1032	6576	0.157				
12/01/2008	35.3	1044	6927	0.151		146.8	331.0	
15/01/2008						60.7	652.3	
17/01/2008	36.6	1107	6651	0.166				
06/03/2008	34.2	1060	6615	0.160				
20/03/2008						100.7		
03/04/2008						151.5	1465.0	
10/04/2008	35.4	1013	6746	0.150				
26/04/2008	34.3							
07/05/2008						548.9	2236.0	
13/05/2008						713.4	1853.0	
15/05/2008	37.4	1045	6940	0.151				
11/06/2008	35.0	1055	7094	0.149		463.9	2121.0	
10/07/2008	25.9	1046	7018	0.149		44.7	451.0	
09/08/2008	16.3							
11/08/2008						47.3	959.0	
29/08/2008	15.7	1010	6739	0.150				
16/09/2008	22.4	1034	6765	0.153		120.0	2003.0	
14/10/2008	23.2	988	6879	0.144				
14/11/2008						8.6	155.0	
27/11/2008	23.8	1012	6599	0.153				
22/12/2008	30.0							

Note seismicity data has not been added due to space constraints.

Appendix C – Poás Monitoring Data

Table C.1: Monitoring data from Poás from 1960 to 1998 (from Rowe *et al.*, 1992a; Stevenson, 1992; Martínez *et al.*, 2000).

Date	Lake Temperature (°C)	Mg^{2+} (ppm)	Cl^- (ppm)	Mg/Cl Ratio	SO_4 (ppm)	$H_2S_xO_6$/Cl Ratio
08/08/1960	33	78	2760	0.028	3510	0.3080
15/03/1978	50					
15/06/1978	52					
15/09/1978	58					
15/10/1978	70					
15/12/1978	50					
15/02/1979	40					
15/03/1979	40					
15/05/1979	38					
15/07/1979	55					
15/08/1979	35					
15/10/1979	60					
15/11/1979	65					
15/12/1979	58					
15/01/1980	55					
15/02/1980	50					
15/03/1980	48					
15/05/1980	44					
15/06/1980	30					
15/08/1980	40					
15/09/1980	45					
15/10/1980	45					
15/11/1980	45					
15/12/1980	45					
15/01/1981	40					
15/02/1981	50					
15/03/1981	48					
15/04/1981	45					
15/06/1981	51					
15/07/1981	48					
15/08/1981	46					
15/09/1981	48					
15/10/1981	48					
15/11/1981	42					
15/12/1981	54					
15/01/1982	47					
15/02/1982	48					
15/03/1982	47					
15/04/1982	50					
15/05/1982	50					
15/06/1982	50					
15/07/1982	49					
15/08/1982	50					
15/09/1982	56					
15/10/1982	54					
15/11/1982	41					

15/12/1982	40						
22/01/1983	57			18000			0.0000
14/02/1983	54						
15/03/1983	56						
07/04/1983	60			18000			0.0000
11/05/1983	53			18000			0.0000
15/06/1983	57			21000			0.0000
05/07/1983	52			22500			0.0000
28/07/1983	50			22500			0.0000
26/08/1983	52			28000			0.0000
28/09/1983	58			18000			0.0000
02/10/1983	60			21000			0.0000
14/11/1983	56						
01/12/1983	56			29000			0.0000
26/01/1984	51			26000			0.0000
14/02/1984	51						
08/03/1984	54			23000			0.0000
05/04/1984	50			20000			0.0000
27/04/1984	49			26000			0.0000
14/05/1984	49						
05/06/1984	50			25000			0.0000
01/08/1984	48			24000			0.0000
28/08/1984	48			25000			0.0000
15/09/1984	50						
19/10/1984	48			25000			0.0000
27/11/1984	48		780	23700			0.0000
28/11/1984	48		780	23700	0.033	57700	0.0251
15/12/1984	48						
23/01/1985	44		790	25400			0.0000
24/01/1985	44		790	25400	0.031	49500	0.1619
14/02/1985	44						
01/03/1985	43						
19/03/1985	44		710	24700			0.0000
20/03/1985	44		710	24700	0.029	48200	0.1383
14/04/1985	44						
06/05/1985	44		690	22000	0.031	55000	0.0914
04/06/1985	48						
25/07/1985	46						
22/08/1985	45		600	21100	0.028	54200	0.1543
09/09/1985	45						
09/10/1985	45		580	20700	0.028	52900	0.1134
28/11/1985	45						
13/12/1985	45						
14/01/1986	45						
03/02/1986	38		560	16500			0.0000
04/02/1986	38		560	16500	0.034	36900	0.1893
14/02/1986	39						
15/03/1986	39						
03/04/1986	38						
02/05/1986	38		530	16500	0.032	40100	0.2550
15/06/1986	48						
09/07/1986	52						
22/08/1986	52		550	18900			0.0000
23/08/1986	52		550	18900	0.029	41200	0.2068
23/09/1986	56						

31/10/1986	54	500	23200	0.022	52000	0.1204
01/11/1986	54	500	23200			0.0000
14/11/1986	54					
23/12/1986	54					
09/01/1987	61	550	30400			0.0000
10/01/1987	61	550	30400	0.018	64400	0.1176
14/01/1987	58					
16/02/1987	62	620	33700			0.0000
27/02/1987	62	620	33700	0.018	78600	0.0274
18/03/1987	62	680	35900			0.0000
19/03/1987	62	680	35900	0.019	82900	0.0035
14/04/1987	64					
14/05/1987	62					
15/06/1987	70					
11/07/1987	68	560	28900			0.0000
12/07/1987	68	560	28900	0.019	64400	0.0782
23/07/1987	70					
26/07/1987	66	830	44900			0.0000
28/07/1987	66					
14/08/1987	65					
09/09/1987	65		43400			0.0000
10/09/1987	65	840	43400	0.019	108000	0.0000
29/10/1987	65					
22/11/1987	60					
26/11/1987	61	500	48000			0.0000
27/11/1987	61	500	48000	0.010	101000	0.0000
15/12/1987	62					
27/12/1987	66	830	44900	0.018	103000	0.0002
15/01/1988	64	840	59300			0.0000
16/01/1988	64	840	59300	0.014	127000	0.0000
14/02/1988	64					
01/03/1988	60	740	51300			0.0000
02/03/1988	60	740	51300	0.014	118000	0.0000
05/04/1988	58					
13/04/1988	65					
11/05/1988	60					
23/06/1988	65	1040	73100			0.0000
24/06/1988	65	1040	73100	0.014	175000	0.0000
05/07/1988	65					
03/08/1988	65					
01/09/1988	75	1520	44200			0.0000
02/09/1988	75	1520	44200	0.034	196000	0.0000
05/10/1988	75					
25/10/1988	65	1420	47400			0.0000
26/10/1988	65	1420	47400	0.030	192000	0.0000
10/11/1988	75					
15/12/1988	75					
13/01/1989	82					
21/01/1989	79					
07/02/1989	87	3590	28000	0.128	286000	0.0000
14/02/1989	79					
03/03/1989	82	3650	27200	0.134	233000	0.0000
14/04/1989	82					
31/05/1989	80	2470	25100	0.098	124000	0.0046
09/06/1989	77	2780	27700	0.100	188000	0.0091

16/06/1989	80	2670	34900	0.077	174000	0.0016
22/06/1989	80	2840	40600	0.070	175000	0.0000
26/07/1989	85	2740	46500	0.059	175000	0.0079
03/08/1989	85	3420	45400	0.075	163000	0.0335
08/08/1989	87	2040	46300	0.044	167000	0.0238
17/08/1989	87	2500	39200	0.064	99300	0.0000
24/10/1989	82	2630	64100	0.041	154000	0.0000
26/01/1990	85	1630	52000	0.031	109000	0.0008
21/02/1990	90	2070	95200	0.022	103000	0.0003
17/03/1990	79	2650	63100	0.042	165000	0.0000
10/07/1990	80	1600	90000	0.018	96700	
13/09/1990	80	2290	129000	0.018	102000	
09/01/1993	65		49100		54000	
06/02/1993	70		56100		58000	
20/02/1993	60		75900		84000	
04/03/1993	60		75500		65000	
14/04/1993	60		61200		55000	
16/04/1993	60		24500		47000	
14/05/1993	63		85600		91000	
11/06/1993	65		36400		35700	
09/09/1993	64		29600		50400	
22/10/1993	60		27600		45900	
10/12/1993	60		25300		40700	
04/02/1994	60		32800		62100	
12/03/1994	55		65500		83100	
11/05/1994	65		12700		19000	
19/05/1994	65		17700		17500	
04/06/1994	70		25500		19400	
10/06/1994	65		24000		9630	
08/07/1994	65		16500		24900	
30/08/1994	60		10100		19200	
09/09/1994	65		15600		15300	
21/10/1994	60		8470		17000	
15/11/1994	55		7640		11000	
06/01/1995	50		10200		16000	
03/02/1995	47		10100		166000	
10/03/1995	42		7780		20400	
28/04/1995	41		8000		21900	
19/05/1995	43		5240		10800	
02/06/1995	39		5180		9970	
30/06/1995	39		4740		9510	
26/08/1995	36		5010		9510	
22/09/1995	34		4390		8870	
20/10/1995	30		2800		6220	
17/11/1995	26		3710		7050	
15/12/1995	30		3632		6860	
05/01/1996	30		3590		9060	
26/01/1996	30		3370		7310	
30/01/1996	26		3370		6680	
23/02/1996	27		2630		4480	
22/03/1996	30		3370		6270	
12/04/1996	34		4230		5970	
26/04/1996	36		3910		5290	
10/05/1996	36		4010		5180	
18/05/1996	39		4280		5410	

31/05/1996	42		4330		5060	
14/06/1996	45		4390		7000	
24/07/1996	36		4460		7520	
08/08/1996	34		4510		6970	
30/08/1996	36		4370		7020	
27/09/1996	40		4320		6780	
05/11/1996	35		5350		7170	
28/11/1996	31		5110		6790	
18/12/1996	29		3650		4870	
07/01/1997	32		5750		6880	
04/02/1997	31		3850		5110	
03/03/1997	29		3260		4410	
04/04/1997	29		4330		4870	
17/04/1997	28		4230		4640	
21/04/1997	25		4570		4990	
14/05/1997	29		4420		4640	
04/06/1997	35		4280		4750	
02/07/1997	32		4620		4870	
28/07/1997	31		4735		5120	
05/08/1997	33		5290		4640	
19/08/1997	35		5750		5320	
03/10/1997	35		7580		6340	
17/10/1997	35		5980		6220	
04/11/1997	34		7800		6460	
25/11/1997	35		7660		6850	
28/11/1997	35		6900		6400	
23/09/1998	65		24000		27000	